Technical paper for ISA Workshop on
Polymetallic Nodule Mining Technology
-Current Status and Challenges Ahead-
Feb. 18-22, 2008, Chennai, India

Model mining units of the 20th century and the economies

(production requirements, area requirements and vertical integration)

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ABSTRACT

Manganese nodules on deep ocean floor have received attention as future resources for Co, Ni, Cu, and Mn these 40 years. The mining and metallurgical processing technologies studied these 40 years have been reviewed and re-examined on the basis of current interests, technologies, and economies by the author. The preliminary results of economic evaluation at the three timings, such as the last 1990s, 2004, and 2006, are introduced. Comparing with the nodule mining venture, advantages and disadvantages of cobalt-rich manganese crust and the Kuroko-type seafloor massive sulfide ones are also introduced.

KEYWORDS: Deep-sea mining, economic feasibility, manganese nodule, metallurgical processing, sensitivity analysis.

INTRODUCTION

Both manganese nodules on the deep ocean floors of the Pacific and Indian oceans, as well as cobalt-rich manganese crusts (CMC) on the Pacific ocean seamounts, have received attention since the 1970s as potential sources for strategic metals such as Co, Ni, Cu, and Mn, due to their vast distribution and relatively higher metal concentration (Mero, 1965; Cronan, 1980). Because similar metals are contained in both, future needs may require that we select between the two.

Several registered Pioneer Investors have already identified promising sites in the deep-sea regions for manganese nodule mining (ISA, 1998), and appropriate mining technologies have been developed during the last 40 years by the international consortium and several nations (Welling, 1981; Kaufman et al., 1985; Bath, 1989; Charles et al., 1990; Yang and Wang, 1997; Yamada and Yamazaki, 1998; Hong and Kim, 1999; Muthunayagam and Das, 1999). The mining feasibility for manganese nodules, including an economic evaluation, has been examined in detail (Andrews et al., 1983; Hillman and Gosling, 1985; Charles et al., 1990).

On the other hand, the only reported information on potential areas for CMC has been scientific in nature (Cronan, 1984; Clark et al., 1984; Misawa et al., 1987; Pichocki and Hoffert, 1987); only one systematic feasibility study has been published (Hawaii DPED, 1987). The technical and economic advantages and disadvantages of CMC have not yet been evaluated. Lack of detailed information about the distribution characteristics, mining technologies, and ore processing technologies have been the reason.

The Kuroko-type seafloor massive sulfides (SMS) in the western Pacific have received much attention as sources for economic recovery of Au, Ag, Cu, Zn, and Pb. Since the end of the 1980s, the Kuroko-type SMS have been found in the back-arc basin and on oceanic island-arc areas. In the Okinawa Trough and on the Izu-Ogasawara Arc near Japan (Halbach et al., 1989; Kato, et al., 1989; Iizasa et al., 1999), in the Lau Basin and the North Fiji Basin near Fiji (Fouquet et al., 1991; Bendel et al., 1993), and in the East Manus Basin near Papua New Guinea (Kia and Lasark, 1999), typical representatives are found. They yield a higher concentration in Au and Ag than the SMS found in ocean ridge areas (Haymon and Kastner, 1981; Malahof, 1981; Hekinian et al., 1983; Rona et al., 1984; Hekinian and Bideau, 1985; Rona, 1985). Similar formation processes with the Kuroko ore deposits on-land in Japan have been expected and outlined by many researchers (Sillitoe, 1982; Scott, 1985; Halbach et al., 1989; Iizasa et al., 1999).

PREVIOUS RESEARCH

Manganese Nodule

Many scientific, technical, and economical publications are available on manganese nodules, mostly because they have been considered the primary commercial target (Mero, 1965; Cronan, 1980). The geological distribution characteristics have been studied in depth by numerous researchers (Craig and Andrews, 1978; Andrews and Friedrich, 1979; Friedrich et al., 1983; von Stackelberg and Beiersdorf, 1991). However, very little detailed information on the first mining target areas in the Clarion Clipperton Fracture Zones has been available (Morgan et al., 1992; ISA, 1999), even though the international consortia have authorized their sites with US domestic law (Padan, 1990) and the Pioneer Investors with ISA (1998) there. Without this type information, basic factors had to be assumed in some previous feasibility studies of the development (Andrews et al., 1983; Hillman and Gosling, 1985; Charles et al., 1990).

In the twenty years following the R&D activities with the international consortia in the 1960s and 1970s (Welling, 1981; Kaufman et al., 1985; Bath, 1989), mining technologies have been developed by several national projects (Charles et al., 1990; Yang and Wang, 1997; Yamada and Yamazaki, 1998; Hong and Kim, 1999; Muthunayagam and Das, 1999). Though some of the consortium's mining technology results have been reported (Clauss, 1978; Burns and Suh, 1979; Grote and Burns, 1981; Chung et al., 1981; Kollwentz, 1990), most of the technically important data remain secret. On the other hand, many publications have been available from the national projects and other studies on seafloor nodule miner design and operation (Li and Zhang, 1997; Yasukawa et al., 1999; Hong et al., 1999; Yamazaki et al., 1999; Deepak et al., 2001), the hydraulic lifting characteristics of nodules in pipeline (Bernard et al., 1987; Saito et al., 1991; Xia et al., 1997; Yoon et al., 2000; Chung et al., 2001), and the hydro-dynamics of the pipeline (Aso et al., 1994; Chung et al., 1994; Cheng and Chung, 1997; Ohta and Morikawa, 1997; Handschuh et al., 2001).

Some important results and reviews of nodule metallurgical processing have also been reported (Agarwal et al., 1979; Hubred, 1980; Black, 1982; Kim and Park, 1997; Kojima, 1997; Zhong et al., 1999; Das, 2001). Most of the proposed processing methods were well examined in Kojima (1997), and an advantage of the smelting and chlorine leach method was concluded in the study. The mining feasibility, including an economic evaluation, was examined in detail (Andrews et al., 1983; Hillman and Gosling, 1985; Charles et al., 1990). The feasibility on the inside of Cook Islands EEZ was presented (Soreide et al., 2001). A comparative summary of the studies is shown in Table 1.

Table 1 Comparison of economic evaluation of manganese nodule development

	Soreide et al. (2001) High-Temperature and High- Pressure Sulfuric Acid Leach Process			**Hillman and Gosling (1985)** Cuprion Ammoniacal Leach Process			**Andrews et al. (1983)** Reduction and Hydrochloric Acid Leach Process			**Charles et al. (1990)** Reduction and Hydrochloric Acid Leach Process		
	Mining (wet)	Trans. (dry)	Process. (dry)	Mining (wet)	Trans. (dry)	Process. (dry)	Mining (wet)	Trans. (dry)	Process. (dry)	Mining (wet)	Trans. (dry)	Process. (dry)
Production (t/y)	1.1M	0.7M	0.7M	4.2M 300d/y	3.0M 300d/y	3.0M 330d/y	2.3M 300d/y	1.5M 300d/y	1.5M 330d/y	2.3M 250d/y	1.5 M	1.5 M
Capital cost	127M$	93M$	271M$	590M$	310M$	727M$	180M$	176M$	513M$	282M$	188M$	470M$
Capital cost ratio	26%	19%	55%	36%	19%	45%	21%	20%	59%	30%	20%	50%
Equity/Loan	30 : 70			100 : 0			100 : 0			50 : 50		
Operating cost **Loan interest** **Survey cost**	21.8M$ 8% 1.9M$	13.5M$	22.9M$	77M$ 0% 3M$	37M$	111M$	45M$ 0% 6M$	25M$	165M$	48M$	36M$	156M$
Operating cost ratio	38%	23%	39%	34%	16%	50%	19%	11%	70%	20%	15%	65%
Metal Co Ni Cu Mn	**Price** $ 20/lb $ 3.33/lb $ 1/lb	**Recovery** 83% 98% 97%	**Product** 2,652t/y 2,548t/y 1,890t/y	**Price** $ 8.53/lb $ 3.62/lb $ 1.17/lb	**Recovery** 65% 92% 92%	**Product** 5,070t/y 36,708t/y 28,704t/y	**Price** $ 5.5/lb $ 3.75/lb $ 1.25/lb $ 0.4/lb	**Recovery** 85% 95% 95% 93%	**Product** 3,375t/y 18,525t/y 15,675t/y 404,550t/y	**Price** $ 6.8/lb $ 3.6/lb $ 0.95/lb $ 0.3/lb	**Recovery** 85% 95% 95% 93%	**Product** 3,525t/y 19,730t/y 17,810t/y 382,500t/y
Taxes **NPV** **IRR**	10% -81M 9.6%			Total 29% 7.4%			46% 6.4%			12%		

Cobalt-rich Manganese Crust

Less information is available for CMC, though their resource potential has been of great interest (Halbach, 1982; Manheim, 1986). In potential mining areas, only scientific data has been available (Halbach et al., 1982; Hein et al., 1985a; Hein et al., 1985b; Cronan et al., 1991; Cronan and Hodkinson, 1991 and 1993). The economic evaluation is insufficient; only one systematic feasibility study has been published (Hawaii DPED, 1987). The reason lies in the scarcity of published research on the engineering distribution characteristics (Morgan et al., 1988), the mining technologies (Halkyard, 1985; Latimer and Kaufman, 1985), and the ore processing technologies (Haynes et al., 1987; Hirt et al., 1988).

Because the information remains insufficient, it is difficult to evaluate the economic potential of CMC with absolute certainty. However, it seems possible to conduct a preliminary economic comparison with manganese nodules, thanks to reports on research in key areas, such as geological and engineering distribution characteristics (Yamazaki et al., 1990; Yamazaki et al., 1993; Yamazaki et al., 1994; Yamazaki et al., 1996; Usui and Someya, 1997; Yamazaki and Sharma, 1998; Yamazaki and Sharma, 2000), mining technologies (Aso et.al, 1992; Yamazaki et al., 1995; Chung, 1996; Chung, 1998), and ore dressing technologies (DOMA, 1998). The most important of these studies is the experimental study of ore dressing methods for cobalt-rich manganese crust samples (DOMA, 1998). Four different methods, including froth flotation, magnetic separation, gravity concentration by vibration table, and color intensity separation, were tested on the actual samples recovered from different seamounts in the study. The effectiveness of all the ore dressing methods, with the exception of color intensity separation, was partially proved with the study, and some basic data for the economical evaluation were collected.

Kuroko-type Seafloor Massive Sulfide

During the feasibility study for the development of the Red Sea sulfide mud (Amman, 1985; Nawab, 2001), much information was gathered. Further, some technical R&D and a mining test in-situ were conducted to back up the technical and economic evaluation. In case of the Kuroko-type SMS, however, less information for the evaluation was available in the 20th century.

The higher Au, Ag, and Cu contents in the Kuroko-type SMS have increased the interests for profitable mining operation in the 21st century, which have been under consideration by private companies (Malnic, 2001; Nautilus Minerals HP; Neptune Minerals HP). Their important information necessary for the resource potential evaluation and commercial mining feasibilities are being clarified.

MODEL FOR ANALYSIS

Outline

A preliminary economic evaluation model for manganese nodules has been created on the basis of previous feasibility reports (Andrews et al., 1983; Hillman and Gosling, 1985). The evaluation models for CMC and the Kuroko-type SMS have been developed by modifying the model for manganese nodules and referring to the one existing CMC feasibility study (Hawaii DPED, 1987). In addition to considering the geological and geophysical differences between manganese nodules, CMC, and the Kuroko-type SMS, ore dressing subsystems for CMC and the Kuroko-type SMS are installed in the models. The other subsystems and the components are assumed to be almost similar; for example, the same metallurgical processing method is selected in the two models for manganese nodules and CMC. Outlines of the models and the flowchart of mined ore are introduced in Fig. 1 for manganese nodules, and in Fig. 2 for CMC and the Kuroko-type SMS.

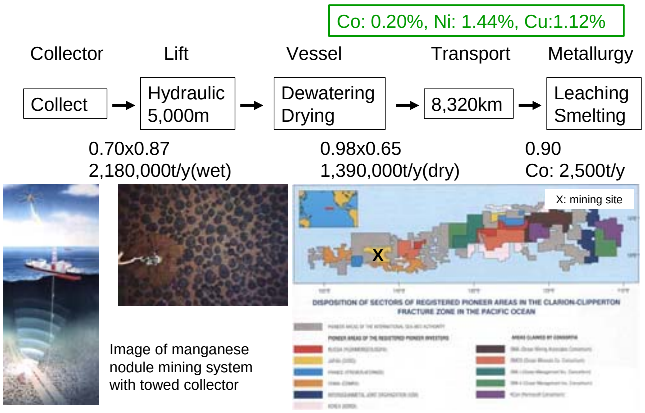

Fig. 1 Evaluation model for manganese nodule mining

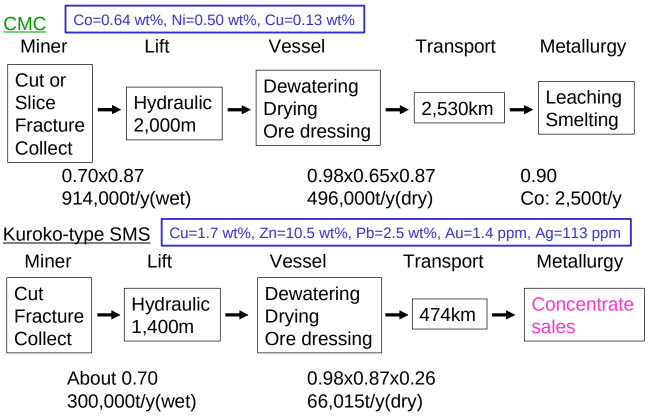

Fig.2 Evaluation models for CMC and Kuroko-type SMS mining

System Components

Outline

Basic subsystems and components for the developments are chosen and identified with reference to Hillman and Gosling (1985) and the technological R&D results introduced in the previous section. Andrews et al. (1983) is sometimes used to make up for gaps in the information from Hillman and Gosling (1985).

Mining Subsystem

The mining subsystem is composed of a seafloor miner, a pipeline with submersible hydraulic pumps for nodule lifting, and a mining vessel. The miner used for the nodule mining is assumed to be a towed collector with the hydraulic nodule pick-up device developed in Japan's national project (Yamada and Yamazaki, 1998). A self-propelled miner with mechanical slicing and crushing, along with hydraulic pick-up devices, are assumed for CMC mining and the similar one for the Kuroko-type SMS mining. The basic components of steel pipe and flexible hose, and the pumps are similar. Their dimensions, strengths, numbers, and capacities are different with the depths and production rates. Except for the ore dressing subsystems, facilities on board the mining vessel are similar in the three; these include the handling units for deployment and retrieval of submersible equipments, their support during the mining operation, electric power generators, dewatering units, drying units, ore storage, control units, and general facilities for cruising and mining operations. Ore lifted from the seafloor to the vessel is separated from the water in the dewatering unit. Water in the pore structure of the ore is excluded in the drying unit, further reducing the weight. The installation of this unit onboard the mining vessels is a new idea presented in Soreide et al. (2001) and important for saving the operation cost thereafter.

Ore Dressing Subsystem

The ore dressing subsystems for CMC and the Kuroko-type SMS are considered to be the most important ones in the models. The subsystems eliminate the waste rock from mined ore and are necessary for reducing the weight of the ore to be transported and processed. Because the system operation for CRC was examined by DOMA (1998) and the one for the Red Sea sulfide mud in the technical R&D (Amman, 1985; Nawab, 2001), these results are referred and introduced into the models. Both in the models the waste rock dumping into the ambient water column is assumed.

Transportation Subsystem

Transportation by carrier vessel from the mining site to a metallurgical processing plant located near Tokyo in Japan is basically assumed. The vessel size and number depend on production rates from the mining and ore dressing subsystems.

Metallurgical Processing Subsystem

The smelting and chlorine leach method concluded in Kojima (1997) is selected for the basic metallurgical processing for manganese nodules and CMC. The high recovery of metals, ease of separating metals from metal-bearing solution, and repeatable use of sulfur are its advantages. The sale of the concentrates to some existing sulfide customer smelters in Japan is assumed for the Kuroko-type SMS after desalting of the mined ore.

Production Scale

The world consumption of produced metals was not considered as a factor in deciding the production scales used in the old feasibility studies (Andrews et al., 1983; Hillman and Gosling, 1985; Charles et al., 1990). Soreide et al. (2001), however, chose cobalt as the target production scale metal because the cobalt market is the smallest of the produced metals. They set about 2,500 t/y as the optimal cobalt metal production scale, equal to about 10 % of the world's annual consumption in the last 5 years in the 1990s (Roskill IS, 2000). This assumption seems reasonable for the evaluation criterion, as it keeps quantities comparable with those in the economical evaluation. Therefore, the production scales of the models for manganese nodules and CMC in this study are set as equivalent for 2,500 t/y of cobalt metal. The production scales of the models are calculated in reverse from the 2,500 t/y, the recovery efficiencies of each subsystem and unit, and the cobalt content in the ore. The calculation balances are shown in Fig. 1 for the manganese nodules and in Fig. 2 for CMC. The recovery efficiencies are defined in the following section. The production scale of 300,000 t/y in wet weight is selected from the duration of the production (approximately 20 years) and the amount of the Kuroko-type SMS ore body (approximately 9,000,000 metric tons in wet weight, whereas it is assumed that only two-third of the ore body will be recovered).

Geophysical and Geological Setting

Manganese Nodule

The primary geophysical and geological factors necessary for the technical modeling and the economical evaluation for manganese nodules are as follows:

Site location: N10°, W147°
Site depth: 5,000 m
Nodule population: 10 kg/m^2 in wet weight
Metal content in nodule: 0.20 % in Co, 1.44 % in Ni, and 1.12 % in Cu in dry weight
Nodule density: 2.0 in wet bulk
Nodule water content: 0.35 in weight.

Cobalt-rich Manganese Crust

The factors necessary for the modeling and the evaluation for CMC are as follows:

Seamount location: N17°, E157°
Seamount depth: 2,000 m
Crust abundance: 100 kg/m^2 in wet weight
Crust thickness: 50 mm
Metal content in crust: 0.64 % in Co, 0.50 % in Ni, and 0.13 % in Cu in dry weight
Crust density: 2.0 in wet bulk
Crust water content: 0.35 in weight
Substrate density: 2.5 in wet bulk
Substrate water content: 0.1 in weight
Substrate weight ratio in excavated wet ore: 0.194
Rock content in substrate: 0.6 in limestone, and 0.4 in basalt.

Kuroko-type Seafloor Massive Sulfide

The factors necessary for the modeling and the evaluation for the Kuroko-type SMS are as follows:

Site location: N32°06', E139°52'
Site depth: 1,400 m
Amount of ore body: 9 million tons in wet weight
Assumed metal contents in mined ore: 1.66 %, in Cu, 10.5 % in Zn, 2.45 % in Pb, 1.4 ppm in Au, and 113 ppm in Ag in dry weight
Ore density: 3.2 in wet bulk
Ore water content: 0.128 in weight
Ore compressive strength: 3.1-38 MPa
Ore tensile strength: 0.14-5.2 MPa

Technical Setting

Some technical settings have already been introduced in previous sections. The most important point to be mentioned is the recovery efficiencies of each subsystem and unit introduced in Figs. 1 and 2. The sweep efficiency, defined as the portion of the mining site covered with the seafloor collector or miner, is not included in the recovery efficiencies; while it affects the duration of site mining, it does not affect the total energy consumption, as larger miners consume more energy.

The first loss introduced in this study is the *excavation efficiency*, defined as the portion of excavated ore actually recovered from the collector or miner track. For safety, the hydraulic nodule pick-up device sometimes is not used while the collector traverses the seafloor. The excavation efficiency is temporarily assumed as 0.7 for the collector and the miner, as suggested in a previous study (Hillman and Gosling, 1985). The second introduced loss is the *pick-up efficiency*. Larger and smaller nodules or fragments of crusts are eliminated at the pick-up device and the sediment separator. The third loss is the *dewatering efficiency*. A small portion of the lifted ore is lost with the water in the dewatering unit. These two efficiencies are set 0.87 and 0.98, respectively on the basis of Yamazaki et al. (1999 and 1991). The *drying efficiency* is deduced from the water content of the nodule, the crust, and the substrate defined in the previous section. The *ore dressing efficiencies* for the crust and the substrate differ according to the separation techniques, the substrate ratio, and the rock content in the substrate. Using the limited results from DOMA (1998), they are set as 0.93 for the crusts and 0.78 for the substrate. The *leaching efficiencies* in the metallurgical processing—namely, 0.90 in Co, 0.97 in Ni, and 0.94 in Cu—are borrowed from Kojima (1997). In case of the Kuroko-type SMS, the total of the *excavation efficiency* and the *pick-up efficiency* is roughly assumed 0.7. The *drying efficiency* is deduced from the water content of the Kuroko-type SMS samples defined in the previous section. The *ore dressing efficiencies* are the same as 90% of metal yields in Cu, Zn, Pb concentrates of the Kuroko ore data in Iijima (1967), because a seawater froth floatation is assumed in the ore dressing process.

The last important point in the models is the operation times of each subsystem. They are set at 300 days per year for all the subsystems in manganese nodule and CMC models at sea and 330 days per year for the processing subsystems, as in previous studies (Andrews et al., 1983; Hillman and Gosling, 1985). In case of the Kuroko-type SMS, they are set at 250 days per year for all the subsystems at sea, as a main stream of the Kuroshio Current of which the speed is 3-5 knots is close to the site. It is expected difficult to keep the mining system at an exact position against the strong current in some cases. For on-land subsystems, 360 days per year are set, as the operation days of the customer smelters are in this range.

ECONOMICAL MODELING

Outline

The whole development period is 25 years for manganese nodules and CMC, and 23 years for the Kuroko-type SMS. No inflationary factors for capital and operation costs or metal prices are considered during this period. The operating costs are recalculated with the economic factors in the three evaluation timings, but the capital costs for mining system, ore dressiing, transportation, and metallurgical processing are not. Only the continuing expenses and working capital are recalculated in the initial investment costs. The total investment is covered by 30% equity and 70% loan. The cost elements are given as follows: 1) Variable, 2) Depreciation, 3) Repair, 4) Insurance, 5) Labor, 6) Interest, 7) General and administrative, 8) Miscellaneous expenses, 9) Taxes (property, excise, corporate, and local).

Differences in metal prices and economic factors at the three evaluation timings, such as the last 1990s, 2004, and 2006, used in the analyses are summarized in Tables 1 and 2.

Table 1 Differences in metal prices used in analyses

(http://www.lme.co.uk,
http://www.jogmec.go.jp/data/data_2_3.html and (in Japanese),
http://gold.tanaka.co.jp/commodity/souba/index.php (in Japanese))

Metal	1995-1999	2004	2006
Cobalt	US$ 15/lb, US$ 20/lb, US$ 25/lb, US$ 30/lb	US$ 26.8/lb	US$ 16/lb
Nickel	US$ 3.3/lb	US$ 6.28/lb	US$ 10/lb
Copper	US$ 1/lb	US$ 1.26/lb	US$ 3/lb
Lead	US$ 0.45/lb	US$ 0.37/lb	US$ 0.6/lb
Zinc	US$ 0.55/lb	US$ 0.47/lb	US$ 1.5/lb
Gold	US$ 336.4/oz	US$ 407.5/oz	US$ 600/oz
Silver	US$ 5.2/oz	US$ 6.76/oz	US$ 11/oz

Note: US$ 1/lb = US$ 2.2/kg and US$ 1/oz = US$ 32.154/kg

Table 2 Differences in economic factors used in analyses

(http://www.boj.or.jp/type/stat/dlong/fin_stat/rate/prime.htm (in Japanese),
http://www.federalreserve.gov/releases/H10/hist,
http://www.geocities.jp/tetchan_99_99/ (in Japanese),
http://www.meti.go.jp/statistics/index.html (in Japanese),
http://www1.kyuden.co.jp/agreement_adj_index (in Japanese))

Items	1999	2004	2006
Heavy oil	113 US$/kl	238 US$/kl	415 US$/kl
Coal	30.0 US$/t	35.9 US$/t	50.0 US$/t
Electricity	0.086 US$/kWh	0.11 US$/kWh	0.14 US$/kWh
Calcined lime	66.6 US$/t	85.5 US$/t	110 US$/t
Materials	1	1.25	1.5
Currency	1 US$=121 Yen	1 US$=112 Yen	1 US$=115 Yen
Labor	2,350 US$/mon.	2,327 US$/mon.	2,400 US$/mon.
Interest	8 %	3 %	5 %

Scale Factor

In order to calculate the capital costs required for the production scales selected in this study, the following formula is used.

$$P_1 = P_2 (L_1 / L_2)^n$$

where P_1 = unknown cost of component, or unit selected in this study
P_2 = known cost of component, or unit
L_1 = capacity of component, or unit selected in this study
L_2 = known capacity of component, or unit
n = constant coefficient ranging from 0.6 to 0.7

This formula is generally used in cost estimations of scale-up plants (JATEC, 1993). For the known cost and capacity, the estimates of previous studies (Andrews et al., 1983; Hillman and Gosling, 1985; Hawaii DPED, 1987) are introduced. The selected capacities in this study, such as the production scales and the recovery efficiencies, are introduced to the formula, too. The constant coefficient is given as 0.6 in this study.

CALCULATED RESULTS

The initial investment costs for the three mining ventures are summarized in Tables 3-5. Because the construction and test-production periods, 3-5 years, are covered by the working capital, the values in Tables 3-5 are relatively high. All the cost increases are mainly due to the increase in the heavy oil price. However, the other economic factors also became expensive. The recalculated operating costs are summarized in Tables 6-8.

Table 3 Comparison of initial investments in nodule mining

Subsystem	**Manganese nodules** with production scale 2,200,000 t/y		
	Capital costs		
Mining system	202.6		
Mineral proc.	-		
Transportation	142.7		
Metallurgical proc.	417.0		
Sub-total	**762.3 M$**		
	with factors in 1999	with factors in 2004	with factors in 2006
Continuing expenses	177.1	133.2	198.6
Working capital	219.8	275.5	355.6
Total investment	**1159.2 M$**	**1171.0 M$**	**1316.5 M$**

Table 4 Comparison of initial investments in CMC mining

Subsystem	**Cobalt-rich manganese crusts** with production scale 910,000 t/y		
	Capital costs		
Mining system	107.3		
Mineral proc.	28.5		
Transportation	45.7		
Metallurgical proc.	224.0		
Sub-total	**405.5 M$**		
	with factors in 1999	with factors in 2004	with factors in 2006
Continuing expenses	127.3	114.6	165.3
Working capital	86.9	119.4	152.8
Total investment	**619.7 M$**	**639.9 M$**	**723.6 M$**

Table 5 Comparison of initial investments in SMS mining

Subsystem	**Kuroko-type seafloor massive sulfides** with production scale 300,000 t/y		
	Capital costs		
Mining system	55.0		
Mineral proc.	19.5		
Transportation	9.6		
Metallurgical proc.	-		
Sub-total	**84.1 M$**		
	with factors in 1999	with factors in 2004	with factors in 2006
Continuing expenses	18.9	20.0	28.9
Working capital	9.1	13.4	17.7
Total investment	**112.1 M$**	**117.5 M$**	**130.1 M$**

Table 6 Comparison of operating costs in nodule mining

Subsystem	**Manganese nodules** with production scale 2,200,000 t/y		
	with factors in 1999	with factors in 2004	with factors in 2006
Mining system	45.4	56.3	71.5
Mineral proc.	-	-	-
Transportation	27.1	39.5	57.5
Metallurgical proc.	53.5	61.6	74.2
Total	**126.0 M$**	**157.4 M$**	**203.2 M$**

Table 7 Comparison of operating costs in CMC

Subsystem	**Cobalt-rich manganese crusts** with production scale 910,000 t/y		
	with factors in 1999	with factors in 2004	with factors in 2006
Mining system	16.9	24.3	31.2
Mineral proc.	4.3	6.7	10.2
Transportation	9.2	11.9	16.0
Metallurgical proc.	19.3	25.4	30.0
Total	**49.7 M$**	**68.3 M$**	**87.4 M$**

Table 8 Comparison of operating costs in SMS mining

Subsystem	**Kuroko-type seafloor massive sulfides** with production scale 300,000 t/y		
	with factors in 1999	with factors in 2004	with factors in 2006
Mining system	6.6	11.0	14.0
Mineral proc.	2.2	3.0	4.3
Transportation	3.4	4.0	5.3
Metallurgical proc.	-	-	-
Total	**12.2 M$**	**18.0 M$**	**23.6 M$**

Table 9 Evaluation results of nodule mining

Case	**Manganese nodules** with production scale 2,200,000 t/y		
	Payback periods (year)	NPV (M$)	IRR (%)
Metal prices in 1995-1999 and economic factors in 1999 (Co: US$ 15/lb)	16.9	-156	4
Metal prices in 1995-1999 and economic factors in 1999 (Co: US$ 25/lb)	11.7	77	10
Metal prices and economic factors in 2004	6.6	584	19
Metal prices and economic factors in 2006	5.7	902	23

Table 10 Evaluation results of CMC mining

Case	**Cobalt-rich manganese crusts** with production scale 910,000 t/y		
	Payback periods (year)	NPV (M$)	IRR (%)
Metal prices in 1995-1999 and economic factors in 1999 (Co: US$ 15/lb)	NA	NA	NA
Metal prices in 1995-1999 and economic factors in 1999 (Co: US$ 25/lb)	11.1	62	11
Metal prices and economic factors in 2004	9.7	105	12
Metal prices and economic factors in 2006	NA	NA	NA

Table 11 Evaluation results of SMS mining

Case	**Kuroko-type seafloor massive sulfides** with production scale 300,000 t/y		
	Payback periods (year)	NPV (M$)	IRR (%)
Metal prices in 1995-1999 and economic factors in 1999	9.4	23	13
Metal prices and economic factors in 2004	12.9	-1	8
Metal prices and economic factors in 2006	3.1	209	61

Positive effects with metal prices and negative ones with economic factors drastically affect the economic validation results as summarized in Tables 9-11. The economic return on CMC mining has become very low because of the cobalt price decrease from 2004 to 2006 and the lower copper and nickel contents. On the other hand, the Kuroko-type SMS mining became amazingly profitable from 2004 to 2006. All metal prices in the Kuroko-type SMS, especially zinc and copper, strongly affect the results. The copper and nickel prices and their higher contents in manganese nodules are the reasons for the economic improvement from 2004 to 2006.

Under the situation of record-breaking metal prices, a Kuroko-type SMS mining venture is active in the territorial sea of Papua New Guinea (Nautilus Minerals HP). The project collected much money from mining companies and share markets in 2006 and 2007. The evaluation results of the Kuroko-type SMS mining, introduced in Table 11, may suggest the economic attractiveness of the venture.

Metal prices themselves are the most sensitive factor in the economic analyses. Quick and drastic changes affect the economies, as demonstrated by CMC and the Kuroko-type SMS. The capital costs of mining system, ore dressing, transportation, and metallurgical processing, which are assumed to be the same as the old validation analyses (Yamazaki et al., 2002 and 2003), have become more expensive in 2006. Their negative economic effects need to be clarified in the next detailed studies.

CONCLUDING REMARKS

According to the economic validation analyses using the metal prices and economic factors in 2006, the mining ventures' effects on the economy are clarified. Given Japan's current economic situation, the most attractive and profitable mining ventures are the Kuroko-type SMS and the second manganese nodule in the three deep-sea mineral resources.

There are many uncertain factors in the economic validation analyses. For example, three-metal recovery, such as that of copper, nickel, and cobalt, or four-metal recovery, which includes those three metals plus manganese, have been major discussion topics in the feasibility studies of manganese nodule mining ventures in the past 30 years (for example, Kojima, 1996). Manganese nodule and CMC mining ventures compete with each other in metal production. When one enters actual mining operation, the other one may lose the chance for development. According to the present analyses, the CMC mining venture appears to have no chance for profitable development. However, because large amounts of the distribution are recognized inside the Japan's EEZ (Usui and Someya, 1997) and some additional rare metals and rare earth elements are concentrated in CMC (J.R. Hein, personal communication), continuous R&D efforts in CMC development are also necessary for Japan.

The investment cost of the Kuroko-type SMS mining for Japan is quite small, because no new metallurgical plant is required and the production rate is relatively low. The excavation of the ore body on the seafloor is the easiest among the three deep-sea mineral resources. The largest problem associated with development is the environmental impact assessment on the marine ecosystem. No quantitative data on the background ecosystem are available, and nothing has been clarified about mining's impacts on it. We need to concentrate great efforts in these fields.

Though this study uses only Japan's cases as examples, some other metal-importing countries, such as Korea and some members of the European Union, are in the same situations as Japan. We had better re-evaluate the important potentials of deep-sea mineral resources in the world metal markets.

ACKNOWLEDGMENTS

This study was mainly supported by the Japan Oil, Gas and Metals National Corporation (JOGMEC), Japan. The author would like to express the appreciation to everyone concerned with the

studies introduced in this paper.

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