Advance in Deep-Ocean Mining Systems Research

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ABSTRACT

Advancement in deep-ocean mining technology is a great challenge not only for the resource exploitation, but also for scientific exploration. Future petroleum exploitation will benefit from this advancement. This paper reviews research, development and design aspects of recent technologies for deep-ocean mining systems to recover manganese nodules and cobalt-rich manganese crusts from the seafloor at 800 - 6,000-m depth. First, the seafloor crust is characterized on the basis of preliminary data from the recent survey in the Pacific Ocean. In the last 10 years, few significantly new technologies appear to have evolved in the nodule mining system. However, subsystems have been designed and tested systematically in Japan. Progress has been made in the seafloor miners (or collectors), hoisting systems, and pipe deployment and retrieval dynamics, materials, the system integration, and integrated system control. There was no at-sea test of any deep-ocean mining system since the 1970's. For the crust mining, the seafloor survey has been conducted in some locations of the Pacific Ocean, and the physical characteristics and properties of only a fraction of the crust samples are tested, and more extensive survey is required at various locations of the Pacific to determine its distribution, abundance, and physical characteristics. The United States has a greater geological emphasis, while Japan has a greater engineering emphasis. Also, two crust mining system concepts are discussed. The deep-ocean submersibles will play a role in the ocean mining. Only Japan and India are currently active in the ocean mining program. Japan's national program has been preparing her first at-sea testing with the R & D work since 1981. Finland was developing a nodule mining system in the '80's and was working with the USSR, but the activity of both countries is presently on hold. Presently, several countries, including Korea and China, are also known to have interest in nodule mining and are conducting some exploration, but have no mining systems research.

INTRODUCTION

The deep seabed is one of the potentially most rewarding frontiers that challenges mankind in its quest for knowledge and material achievement. The deep seabed promises to make an enormous contribution to the world's resource base once its potential is fully realized. Manganese nodules (Fig. 1) and cobalt-rich crust (Fig. 2) are resources of current interest for exploration. These are deposited over and beneath the ocean floor at 800 - 6,000-m depth.

Over the last 30 years, international consortia and government enterprises have invested in exploration of deep-ocean hard minerals, manganese nodules in particular, and in research and development of mining technology. The amount of effort has varied during this period as a function of the metal market situation. However, efforts have succeeded to the extent that, today, some selective technologies for subsystems exist for recovering these minerals on a commercial scale. Publicly sponsored entities active recently in the '80's and '90's are from Japan, Finland, the USSR, and India. The industrial consortia were most active in the R & D in the 70's. However, information in the public domain about the technologies from these efforts has scarcely been made available. The earliest research and development, some with at-sea tests, have been conducted by 4 international consortia or groups composed of companies from the United States, Canada, the United Kingdom, the Federal Republic of Germany, Belgium, the Netherlands, Italy, Japan, and France.

As the 60th country ratified the treaty of the Law of the Sea, November 1993, the Law becomes effective in 1994. Only Japan and India are currently active in their national deep-ocean mining program. Japan's program has been preparing her first at-sea testing in 1997. Until commercial mining operations of manganese nodules begin, the mining systems are expected to be continuously updated with the advancement of new support technologies. For the crust mining, the technical challenges are yet to be defined. This review updates that of Chung (1985).

Unit conversion: 1 m = 3.281 ft, 1 ft/s = 0.305 m/s, and 1 mile = 1,609 m.

KEY WORDS: Deep-ocean mining, mining system, advances, manganese nodule, cobalt-rich manganese crust.
molybdenum, vanadium, and titanium) are nodular objects of various sizes and shapes found on the deep-ocean floor between depths of 3,000-6,000 m. More recent commercial interest has been centered on the cobalt-rich manganese crust near the equatorial zone in the North Pacific Ocean.

Manganese nodule mining usually involves coordination or integration of five distinct systems of operations: (1) exploration survey, (2) nodule collection from the seafloor, (3) hoisting to the mining ship, (4) transportation to land, and (5) processing onshore or in the ocean. This paper restricts discussion to only the second, third, and fourth stages, which are of more interest to ocean (mining systems) engineers. Although most of the interested parties, except a few countries, are currently not active or on hold mode in nodule recovery R & D, there are new, recent developments in the assessment of commercial nodule and crust recovery. The paper concludes with discussion of recovery sweep efficiency and the role of recent advancement in support technologies.

CHARACTERIZATION OF MANGANESE NODULE AND CRUST

Manganese Nodules

Engineering and distribution characteristics of deep-ocean resources are much desired information for mining system development. Recent Hakurei-maru No. 2 exploration survey cruises and the subsequent laboratory analysis provide valuable information on the manganese nodules and Co-rich manganese crust.

Size and Strength (TRAM, 1991). The size distribution of nodules affects the design of both the miner and lift pipe system. This information is essential for the design of the seafloor miner intake device and its altitude and collection efficiency. The internal slurry pipe flow can also have problems with throughput efficiency and potential clogging, especially for the hydraulic lift system. Large nodules may be either rejected or crushed. Pump system design can consider either crushing or rejecting nodules. Nodule abrasion is more severe for the airlift than for the hydraulic lift. Depending upon the individual lift systems, the nodules may be crushed at the seafloor level to make the size distribution of nodules suitable to feed to the lift pipe system. The size distribution is measured on the samples from the survey in the Pacific Ocean. The mechanical strength is tested also with the same samples.

Mean long-axis length, short-axis length, thickness and weight taken from more than 1,000 samples, used for the estimation, are 5.5 cm, 4.4 cm, 3.4 cm, and 95.7 g, respectively, and the corresponding standard deviations are 1.8, 1.5, 1.2, and 86.6. Specific size distribution is given in Tables 1 and 2.

<table>
<thead>
<tr>
<th>Long-axis length</th>
<th>Distribution between (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 - 6 cm</td>
<td>25</td>
</tr>
<tr>
<td>6 - 8 cm</td>
<td>40</td>
</tr>
<tr>
<td>8 - 10 cm</td>
<td>25</td>
</tr>
<tr>
<td>other lengths</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 1 Length distribution of manganese nodule samples in the Pacific Ocean

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Distribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 - 4 cm</td>
<td>26</td>
</tr>
<tr>
<td>4 - 5 cm</td>
<td>34</td>
</tr>
<tr>
<td>5 - 6 cm</td>
<td>19</td>
</tr>
<tr>
<td>other thickness</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 2 Thickness distribution of manganese nodule samples in the Pacific Ocean

The uniaxial compressive strength of the manganese nodule samples ranges $3 > \sigma > 5$ MPa. The surfaces of nodules are easily breakable when preparing a standard-shaped test specimen, and it was difficult to perform conventional material tests to measure the strength characteristics. Therefore, the uniaxial compressive test was performed with nodules of irregular shape. The test results are analyzed to get normal compressive strength, $\sigma$ (Fig. 3). In the figure, large solid dots indicate the average values of the previous test results (TRAM, 1984). The sample nodule weight influences the strength values of the test. The strength values from the test specimen of 30 to 40 g in (dry) weight appear to be close to conventional uniaxial compressive strength.

Cobalt Rich Manganese Crust

Distribution Characterization and Physical Properties. Exploration surveys on cobalt-rich manganese crusts have been conducted by several

Fig. 1 Deepsea manganese nodule: White trigger weight is 10 cm in diameter.

Fig. 2 Cobalt-rich manganese crusts near Marcus Island
countries from the early '80's, mainly for geological interest. Based on many survey results, the feasibility of crust mining was discussed (Hawaii, 1987). Since 1987, Japan, with her interest in crust mining systems and engineering, has conducted an extensive exploration survey. The survey used not only the conventional survey and sampling techniques, but also newly developed methods, in which an optical method is combined with real-time color video monitoring, stereo photographs and a successful core sampling with a camera device. The survey is to evaluate the crust as a future mineral resource.

Evaluation of the stereo photographs and video data shows a variety of surface features associated with the crusts and nodules on the mid-Pacific seamounts (Yamazaki, 1994a and 1994b). The crust outcrops have a large coverage (up to 100%). Their surface features vary from step-like to lineated and from cobble to nodular type, giving rise to variable relief (from a few centimeters to several meters). The relief is relatively low (a few tens of cm) around the locations with crust outcrops along with nodules, and much less (less than 10-cm relief) in the areas of nodule fields. The microtopography and relief also vary between locations, depending upon the association of sediments with the crusts and nodules, as well as their respective coverage.

The thickness of the oxide layer ranges from less than 1 cm to more than 10 cm, and the substrates of crust deposits and the nuclei of nodules and boulders are basalt, limestone, hyaloclastite, etc. (Hein, 1985).

![Graph](image)

**Fig. 3** Uniaxial compressive strength test of manganese nodules

Physical and engineering properties of crusts and of their substrates are important design parameters for a crust mining system. Density, porosity, and P-wave velocity were measured as the physical properties. Compressive strength, tensile strength, and shear strength were measured as engineering properties, although the quantity of samples was not sufficient to generalize the data. As the crusts and some of their substrates were too weak, it was difficult to prepare conventional test specimens; so substitutional test methods, such as irregularly shaped compression test for the compressive strength measurement and irregularly shaped point load test for the tensile strength measurement, were adopted. In order to avoid the size effect, fragmented specimens with weight ranging from 30 to 50 g in water-saturated condition were used for the laboratory tests. The shear strength was obtained from a direct shear test (Yamazaki, 1994d).

![Diagram](image)

**Fig. 4** Overview of the gravity coring and measurement system

<table>
<thead>
<tr>
<th></th>
<th>Crusts</th>
<th>Substrates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>1.65-2.17</td>
<td>1.44-2.92</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>43-74</td>
<td>7-69</td>
</tr>
<tr>
<td>P-wave velocity (m/sec)</td>
<td>2090-3390</td>
<td>1760-5860</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>0.5-16.8</td>
<td>0.1-68.2</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>0.1-2.3</td>
<td>0.0-18.9</td>
</tr>
<tr>
<td>Shear Strength (MPa)</td>
<td>1.7-2.5</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3** Summary of engineering properties of crusts and their substrates

Drag dredge sampling is usually adopted for the sampling of cobalt-rich manganese deposits. However, it is effective only for boulder and nodule-type deposits and not for the crusts. Very rare fresh-crust-type fragments were torn by the dredging. Therefore, it seems probable that the oxide layer thickness, physical and engineering properties, and metal composition obtained from those samples are not necessarily representative values of the crust deposits at the place, but still valuable information. Although the existence of buried deposits beneath the calcareous sediments was expected, it had not been certificated. Column sampling of the deposits was considered to be a possible solution to this. As described below, a large-diameter gravity corer has been adopted to certificate the existence of buried deposits. Moreover, its instrumentation, by which the deceleration of the corer during penetration into the deposits could be measured, was tried in order to obtain in-situ data of the engineering properties of the deposits (Yamazaki, 1994c).

**Reevaluation of Crust Reserves.** Previously, the crust deposit coverage on the seafloor was evaluated only with the exposed feature, using the photogrametric analysis. But a possible existence of buried crust deposits covered with calcareous ooze has been pointed out for a long time (Hein,
acoustic survey with a 3.5-kHz sub-bottom profiler and a deep-tow by the photograph after recovering the corer. Before the coring, the one-shot deepsea camera was used, so the exact feature of the seafloor, the corer was tested on the Pacific seamount (Yamazaki, 1992b). The corer core cutter was made of steel and expendable. For the trigger weight, a system with a deepsea TV and a stereo steel camera was carried out. The total weight measured 510 kg. The trigger weight, as shown in Fig. 4. Total weight measured 510 kg. The core cutter made of steel and expendable. For the trigger weight, a one-shot deepsea camera was used, so the exact feature of the seafloor, where the corer hit at and the sample was taken from, could be observed by the photograph after recovering the corer. Before the coring, the acoustic survey with a 3.5-kHz sub-bottom profiler and a deep-tow system with a deepsea TV and a stereo steel camera was carried out. The coring point was selected in the area where no outcrop of the crusts had been observed by the TV and very thin or no sediment layer had been recorded by the subbottom profiler.

Several tens of corings were performed, and several crust core samples covered with calcareous sediments were taken from the barren seafloor. Those samples confirmed the existence of the buried crust deposits beneath the sediments.

Reserve Reevaluation. Assuming that a recovery technology can be developed to excavate the buried crust deposits covered with 0.5 – 1.0-m thick sediments, the recoverable reserves will increase greatly. An assumption was made that: (1) the area, where the existence of outcrop of the crust deposits could not be recognized by the TV and the sediment layer could not be measured by the sub-bottom profiler, should be covered with very thin sediment; and (2) the buried crust deposits, which could be excavated, are distributed as the new coring results show. Based on these assumptions, the recoverable reserve was calculated as a test case at some designated seamounts. It showed the the estimated reserve increased to 3 – 5 times of the previous evaluation (Yamazaki, 1992a, 1993).

MINING SYSTEMS INTEGRATION

A deep-ocean mining system is an integration of a seafloor miner (or collector) system, hoist pipe system, ship system and transportation system. The systems, their subsystems and the associated technologies should be compatible for systems integration. The mining system and its position control system should be designed to minimize the possible adverse dynamic influence of the pipe on the track-keeping ability of the miner. Such design would contribute to economical recovery sweep efficiency. The control should also foresee a substantial time lag between the initiation activity at the top end of a pipe and the result of that initiated activity at the bottom end (Chung, Whitney, and Loden, 1981). The terrain of the ocean floor, from which the miner (or collector) recovers the hard-rock minerals, is uneven, abounding in hills, ridges, troughs, rocks, and similar obstacles. Equipment design and operation of the miner and collecting equipment must operate on such terrain. In addition, the operations of mining ships and underwater subsystems are always affected by waves, ocean swells, and currents. The dynamic behavior of the hoisting pipe makes the entire system-control difficult. Equipment design must overcome very high hydrostatic pressure at the seafloor.

Ocean Surface System

Ship System. In view of deep water depth, all ship or surface systems are dynamically positioned. The control system and simulation of integrated ship, pipe, pipe handling, buffer and seafloor miner by Brink and Chung (1981) are still the most comprehensive. For the RCM system, the efficient, nonconventional (e.g. “crabbing”) maneuvering capability is essential for reduced downtime, higher sweep efficiency, and safety of the seafloor equipment. The ship size is a function of the individual mining system, processing methods (at-sea processing or land processing), overall cost, regular maintenance, and daily production rates, so that the operation is economical. Selection of ship-type or semisubmersible-type structure depends on the overall systems requirements and economic feasibility. The heavy lift system of Glomar Explorer (Fig. 5) has not yet been challenged. Large thrusters in the range of 4,500 hp and 6,000 hp, as required previously by Brink and Chung (1981), were not available at that time, but the large gear can now be machined.

The decision of processing on-land or at-sea greatly influences not only the ship size, but also the recovered mineral storage, the ship system design, and shuttle ship requirements for ore transfer and transport. Another major parameter is the tailing disposal in the open sea, as well as coastal processing plants. Japan has selected a 21,120-t semisubmersible-type structure as test platform (Fig. 6) (TRAM, 1991), which probably implies that a land processing is planned.

Pipe Deployment and Retrieval. Quick deployment and retrieval of the pipe system, especially prior to and during the storm, are a very important part of a mineral recovery operation from the seafloor. This is primarily due to the weather window, local seafloor topography, and potential failure of underwater subsystems, equipment and miners. Accurate simulation and monitoring of the pipe bottom or bottom equipment at the start of seafloor equipment touchdown and lifting is a very critical part of pipe dynamics and control operation for the safety of the system. Each consortium had different equipment systems onboard.

![Fig. 5 Glomar Explorer](image)

![Fig. 6 Semisubmersible platform for Japan's test mining](image)
the ship. It appears that recent methods are conventional, and no special attention appears to have been paid to the speed. A submersible can be used to monitor this critical phase of operations. However, the approach of maneuver of the submersible to the pipe or bottom equipment may not be easy, since the velocity of the oscillatory pipe bottom motion can exceed the maneuvering velocity of the submersible. *Glomar Explorer* deploys 300-ft long section pipes, using the tall derrick and heavy lift system. An efficient pipe-handling system should be an automated system. The simpler and reliable the underwater equipment and subsystems, the less mining downtime is likely.

**Dynamic Systems and Control**

Dynamics and systems control (Chung, Whitney and Loden, 1981; Brink and Chung, 1981) play an important role for both nodule and crust recovery from the deep-ocean bed. Miner propulsion and maneuvering on the seafloor are controlled by a miner-control subsystem onboard the ship. Depth requires the mining ship and/or pipe systems to be fully dynamically-positioned. Thruster systems can be either an azimuth or fixed (x,y) system, depending upon which system is more efficient, reliable and economical. With an integrated control system (Brink and Chung, 1981), a slowly moving ship can maintain the most favorable heading and keep the thruster fuel consumption to a minimum during normal mining operations (Schick, 1980). This means the ship would be able to perform a crabbing motion, where "crabbing" means maneuvering in any direction on the ocean surface plane. During the normal mining operations, the ship is controlled, with or without assistance from the buffer control system, so that the pipe-buffer system stays close to the self-propelled miner track (i.e., within the envelope permitted by a link system, which is defined as the steady-state and dynamic motion displacement of the buffer at the free bottom end of the pipe relative to the miner position at any instant on the seafloor). The integrated control can be determined on the basis of the steady-state and transient motion responses of the bottom end of the pipe, as well as on the basis of position-sensing, feedback and control. For a given pipe diameter, a possibility of the pipe vibration beyond a certain mining velocity and induced by vortex shedding exists (Whitney and Chung, 1981).

The ocean mining system should possess track-keeping capabilities. While the drilling and production operation requires its system to be fully dynamically-positioned to stay over a fixed point on the seafloor, the ocean mining system should be controlled to maneuver along or follow moving set-points on the preplanned seafloor mining track. Finally, the control system design should have the capability to accommodate stopping, sudden encounters with obstacles, and adverse terrain. An extensive control system and computer control simulation that meets these stringent requirements of many mining scenarios was performed by OMCO (Brink and Chung, 1981). The entire position control system is housed onboard the ship.

**Control System.** The transient characteristics of the long mining pipe clearly indicate that the control of the ship-pipe-buffer system configuration could comprise four parts: Measurement system, set point management, adaptive controller, and thrust allocation logic. The measurement system is one of the key systems for the deep-ocean operation. This needs to be updated with advances in the electronic, acoustic and image-processing technologies. For the integrated control of the miner, pipe/buffer and ship systems, the inertial guidance system was adopted by Ocean Minerals Co. (Brink and Chung, 1981). Japan's system uses an acoustic system and fiber-optic cables for data transmission (TRAM, 1991).

**Crust Recovery System Concepts**

**Cobalt-rich Crust and Sediment Accumulation.** A recent *Hakurei-maru* No. 2 cruise survey (Yamazaki, 1993) reveals that the cobalt-rich crusts are located not only on the seafloor surface, flat to 20° slope, but also beneath the calcareous sediment layer. So far, the sediment is found to cover crusts with thickness of greater than 1 m. The thickness of the crust near Marcus Island, the Pacific Ocean, is measured to be approximately 5-10 cm and even as much as 20 cm. Both nodules and crusts are located in the same areas. Water depth for the crust ranges from 800 m to 3,500 m, as compared to 3,000 to 6,000 m for the manganese nodules.

In view of these preliminary findings, the mining system design of the pipe and the seafloor crust recovery from 800 - 3,500-m water depth will require design and operational tasks, in addition to the nodule recovery approach:

- crust-fracturing capability,
- associated constraints on the pipe design and operations,
- crust lifting or hoisting to the ship,
- seafloor-equipment capability to operate on steep slope

Unlike the nodules spread on the surface of the 3,000 - 6,000-m ocean floor, the crusts on the basement rock and beneath the ocean sediment need to be fractured for economical lifting to the ocean surface.

For the crust fracturing, two systems, which connects seafloor miner or equipment to the bottom end of a pipe, are discussed (Chung, 1994):

System *I* is to keep the pipe bottom free from the seafloor miner or equipment motion (Fig. 7)

System *II* is that the seafloor miner or equipment motion is subject to the pipe motion (Fig. 8).

The pipe system can be equipped with vibrators or a waterjet device at the seafloor for fracturing purposes. The vibrator can be designed to locate, position and sit on the crust for fracturing and moves its position continuously. Furthermore, the seafloor slope can be steep (Yamazaki, 1993). A waterjet system can be designed to have little influence on the pipe dynamics. The system should be able to overcome problems associated with pipe strength and vibrations, sediment strength and seafloor slope.

![Fig. 7 A nodule mining system of a 18,000-ft pipe system (System I): the equipment on the seafloor is free from the pipe motion (Chung, 1994).](image-url)
Pipe System Concepts (Chung, 1994). Two basic concepts of crust mining pipe systems are considered in this paper. One of the systems is a new, emerging waterjet, which may be of interest for research.

(a) Waterjet Systems I and II. A nonconventional system of waterjet fracturing and collection of the seafloor crusts is a viable concept with recent advances in waterjet technology. With this system, the waterjet equipment can be either free from (Waterjet I, Fig. 7) (Chung, Whitney, and Loden, 1981; Cheng, Chung, and Huttelmaier, 1994), or directly influenced by (Waterjet II) by the pipe bottom motion (Chung, Huttelmaier, and Cheng, 1994). In the "free" case (Waterjet I), reaction forces between the seafloor and equipment are also an important factor for fracture equipment operations.

(b) Vibrator System I and II. For Vibrator System I, a seafloor vibrator, a crust fracturing equipment, can be designed to have no direct influence from or on the pipe motion within design operational limit (Fig. 8) (Chung, Whitney, and Loden, 1981; Cheng, Chung, and Huttelmaier, 1994). For the case of "no-direct influence," the reaction force between the seafloor and the equipment is required for successful fracturing equipment operations. One parameter is vibrator weight against vibrating force. For Vibrator System II (Chung, Huttelmaier, and Cheng, 1994), a seafloor vibrator can be directly connected to and influenced by the pipe bottom motion for fracturing (Fig. 8). The effect of axial equipment vibration on the pipe stress may not be a major design parameter.

Analyses of 3-D motions and stresses of Systems I and II are presented in the references of (a) and (b) above. The analyses used the newly-developed, general FEM code (Chung, Cheng, and Huttelmaier, 1994). The equipment weight versus behavior of the basement rock beneath the crust is one of many parameters to be considered. The sediment layer in the range of 1 m in thickness above the crust may not be a major problem for the equipment design. But the equipment should be designed for sediment ejection and operations on the seafloor slope (Yamazaki, 1993), which was surveyed to have as much crust as that of the flat area, while possessing the capability to perform continuous track-keeping. The design and operational axial vibration frequency is greatly influenced by the eigenfrequencies of the pipe.

Crust Lift. The pipe system can be used for lifting or hoisting the crust pieces by mechanical, hydraulic, or pneumatic (or airlift) means, similar to those proposed for the nodule lift. Specific gravity is almost identical for both nodules and crust. However, the strength is different (Tables 1~3). Depending upon the sizes of the fractured crust pieces, the lift preparation at the seafloor can differ between the nodule and crust systems. A mechanical system of CLB may also deserve a viable mechanical concept. Selection of an eventual concept will depend not only on technical investigation, but also on economics of production.

Nodule Miner (or Collector)

Reliability, mobility, safety, and collection efficiency of the miner (or collector) system are the most important parameters in the mining system. For the nodule mining, there appear to be no new miner systems evolved since the '70's. The ocean mining consortia have been developing different concept systems of unmanned, seafloor nodule miners:

Nodule miner:

- Tow-sled (TS) System
- Continuous Line Bucket (CLB) System
- Remote-controlled, Self-propelled Miner (RCM) System
- Shuttle System

The first two are traditional systems, simpler in design and mechanically more reliable, but lower in sweep efficiency than the RCM system, primarily because of difficulties in miner track-keeping. The CLB system may not meet commercial, target nodule production rates. And, while Japan’s TS system (TRAM, 1991) appears to attempt to increase sweep efficiency by controlling the sled, it seems that the large force on and the dynamic response of the pipe may make it very difficult to control effectively the dynamic influence of the pipe on the sled. The RCM system, one of the systems developed by the Ocean Minerals Company (OMCO)-Lockheed, appears to use the most modern technology. OMCO designed a commercial RCM system, not yet sea-tested. One of OMCO's RCM systems (Figs. 9) proposes a fully automatic position control through sensor feedback information with a manual override option. They are propelled and maneuvered by Archimedeans screws (Schick, 1980). Rauma-Repola (1988) and the French consortium (Herrouin, 1989), respectively, proposed a test mining system in the late '80's, similar in principle to that of OMCO. Rauma-Repola appears to have studied a track-belt system. A scale-model of a shuttle system was tested in the early '80's by a French consortium (Bardy, 1985). It avoids the use of a hoisting pipe; instead, it uses continuous movement of self-propelled, self-ascending and descending shuttle miners whose Archimedeans propulsion principle is very similar to that of OMCO.

An integrated system of the ship maneuvering, the pipe responses and the seafloor miner’s movements can be simultaneously controlled as the miner moves along the pre-planned track. During deployment and retrieval of the pipe and seafloor miner, the ship can be controlled to station-keep over a fixed point on the seafloor. And, during normal nodule-recovery operations, the ship and/or pipe bottom-end can be controlled to maneuver continuously or to track-keep, to turn, etc., staying close to the remote-controlled, self-propelled miner on the seafloor, which keep mining tracks precisely by a set-point management. More details on specific, known mining systems are available through patent information.

At-sea integrated control tests of a remote-controlled miner maneuvering on the seafloor were conducted in the late '70's in the Pacific Ocean with a 3-mile-long pipe deployed from the fully dynamically-positioned mining ship Glomar Explorer (Fig. 5), operated by OMCO. The self-propelled miner, which was connected by a link subsystem to the oscillating free bottom-end of the mining pipe, was...
controlled to self-propel and maneuver successfully at a very slow speed on the uneven seafloor with coordinated control from the mining ship on the surface.

Japan designed a 13-m tow-sled test miner with a pressurized water-flow collecting mechanism. The larger nodules are crushed on the collector for pipe-hoisting (TRAM, 1991). Much work was also carried out to investigate the soil properties in terms of nodule collector motion and the collection mechanism (NIRE, 1991). The uniaxial compressive strength of the manganese nodule samples ranges from $3 > a > 5$ MPa (TRAM, 1991). An at-sea test in the Pacific Ocean is expected in 1997. The nodule collection principles considered are: (1) mechanical pickup, (2) hydraulic pickup, and (3) mechanical-hydraulic pickup. Since the '70's, no at-sea tests of deep-ocean nodule collection have been conducted.

As for the crust miner, waterjet and vibrator systems are proposed among a few concepts (Chung, 1994), and are discussed above. Masuda and Cruickshank (1994) propose a CLB system to collect cobble-type crust from 1,200-m depth. The cobble-type crust is in a form of nodule, and the system was tested in 50-m depth water.

**Lift to the Ocean Surface**

Slurry of nodule-water mixtures can be transported by one of the three hoisting pipe-lift systems: hydraulic system, pneumatic (or air-lift) system, and mechanical system. Although the internal nodule-water slurry was studied by the consortia, there are very few published reports. The important parameters are optimum concentration of nodules or nodule pieces in the slurry, friction factor, wear, etc.

**Nodule Hoist**. The nodules collected by the self-propelled miner are in the form of a mixture of nodules, soil particles and the seafloor water. Nodule preparation is necessary for efficient nodule lift. The buffer is connected at the bottom part of the pipe. It can control the nodule-water mixture ratio for multi-phase flows. The buffer weight would also reduce the steady-state horizontal excursion of the bottom end of the pipe.

The hydraulic system hoists or lifts the nodules in two-phase (nodule-water) flows with pumps in series to the ship through the miner-to-buffer link or pipe, and up the 5,000 m long, nearly vertical pipe string. Deep-submersible pumps, driven by submerged 1,000-1,700 kW electric motors, are developed in Japan for the at-sea test (Fig. 10) (TRAM, 1991), and, at this time, pumps are scheduled to be installed at 1,000 m and 2,000 m below the free surface. Tangential axial shear forces due to the wall friction from the internal flows of crust-water slurry and their effect on the pipe behavior are discussed later in this paper for 18,000-ft (5,486-m) and 4,000-ft (1,219-m) pipes with their bottom end free (Chung, Cheng and Huttelmaier, 1994; Cheng, Chung and Huttelmaier, 1994).

With a pneumatic (or air-lift) system, the nodule lift involves three-phase (nodule-water-air) flows with air bubbles being released at a certain level of the pipe; the depth of the air release is important. The pneumatic system is considered to be simpler, but would consume more power than the hydraulic system. In order for the pneumatic system to

![Fig. 9 A remotely controlled test miner with Archimedean screws (Ocean Minerals Co.)](image)

![Fig. 10 Deep-submersible pump with underwater electrical motor: 9 m in length](image)

![Fig. 11 Performance estimate of nodule lift by hydraulic and pneumatic systems](image)
be efficient, the pipe diameter would have to be larger than the hydraulic system: a relative cost can be found in Fig. 11 (Schick, 1980). For either case, the mixture ratio of nodules in the hoist system needs to be controlled for optimum transport efficiency and to avoid nodule flow plugging (Kumano, 1986). For the optimum efficiency of vertical nodule transport through the pipe, the mixture control can be achieved by such means as buffer, mining speed, etc., for a given nodule distribution per area. Although some claim to have tested at sea with nodules in the Pacific Ocean, no published data have been made available. Saito et al. (1989) propose an empirical formula, reporting an experiment of airlift of solids (nodular objects made of light-weight cement) with a 200-m vertical pipe, offer an empirical formula for slurry volume as a function of solids (nodular objects made of light-weight cement) with a 200-m vertical pipe, offer an empirical formula for slurry volume as a function of solids (nodular objects made of light-weight cement) with a 200-m vertical pipe. Compressed air equipment is completed, and the air-injection point at 1,750 m is planned to be tested (TRAM, 1991). Eventually, the actual nodule lift efficiency needs to be tested in a deep-ocean pipe. A relative comparison of the efficiency between the hydraulic and pneumatic systems are given in Fig. 11 (Schick, 1980).

The mechanical system includes devices such as the CLB system, which provides good reliability but is considered incapable of meeting commercial daily nodule production rates. As for the cobble-type crust miner, however, Masuda and Cruickshank (1994) considers a CLB system to be economical for collection from 1,200-m depth.

Pipe Dynamics

The importance of the axial stress for design was first pointed out by Chung (1981), for which only uncoupled axial stress was investigated for an 18,000-ft (5,486-m) vertical pipe. Recently, Chung, Cheng, and Huttelmaier (1994) point out the inadequacy of the uncoupled dynamic analysis for pipe design.

Recently, Chung, Cheng, and Huttelmaier (1994) investigated the torsional effect on 3-D nonlinear, coupled axial, bending and torsional responses of a 4,000-ft pipe system, using a new nonlinear FEM code on a PC486. It is found that the flow-induced torsional moment on an asymmetric pipe arrangement induces appreciable pipe twist in response to a unidirectional ocean current. Dynamic axial and horizontal motions, when coupled, reduce the mean pipe deflections from the static equilibrium. Resonance frequencies for the present nonlinear coupled motion responses are different from those of the linear vibrations. Axial forces and bending moments change the natural frequencies of vibrations of a pipe column. The internal upward slurry flow reduces the axial stress and increases the horizontal displacements. For Vibrator System II of crust pipe (Fig. 8), random phase takes care of the interactions between the axial motions of pipe top and the seafloor equipment.

For System I analysis of 18,000-ft nodule pipe with its bottom free, 3-D coupling with large static pipe deflections (Fig. 12) shows results similar to the equivalent configuration of the 4,000-ft pipe. Vex in Fig. 12 is the unidirectional current velocity relative to the pipe velocity: 3 ft/s (0.914 m/s) for the top 2,000 ft from the free surface and 1 ft/s (0.305 m/s) below the 2,000-ft level. For both Systems I and II, torsional coupling greatly changes pipe response characteristics and produces substantial pipe twists. The associated static pipe twist angle for System I (Fig. 13) is large and worth considering for design and operations, thread design in particular, and, moreover, is not linear along the pipe. (Mr)h and (Mz)h are the torsional moments by the buffer and the pipe asymmetry, respectively. When the pure axial (z-directional) motion is excited, the axial responses show regular-pattern beating with a period different from the excitation period (Fig. 14). The corresponding axial stresses show similar results with beatings. When excited at periods far removed from the axial resonance, the responses occur at the excitation period, which is similar to that of Chung and Whitney (1981) and Aso (1991, 1992). The coupled axial-bending excitation reduces the amplitudes of the axial displacements and stresses from the pure axial excitation.

Pipe-bottom motion can be controlled so that it stays within an allowed envelope, while continuously moving for precise track-keeping on the seafloor (Brink and Chung, 1980). The full understanding and simulation capability of dynamic behavior of the pipe system is essential for designing an integrated control system.
Motions and Hydrodynamic Forces

There are a few new revelations in hydrodynamics: (1) axial forces due to the axial oscillatory motion of internal slurry flow in the pipe; and (2) the flow-induced torsional moment. Pipe behavior is updated at each node at each time step with preprocessor data of nonlinear normal, steady and transient hydrodynamic loads, which are caused by waves, ship or pipe-top motions in the x-, y- and z-directions, steady current, and large 3-D dynamic pipe motions at the nodes. Furthermore, the analysis of the coupling effect of bending and axial forces accounts for the flow-induced torsional moment and mean lift (lateral force) at the nodes that result from the asymmetric arrangement of the pipe and cables or equipment. Ship dynamics is technologically mature and not reviewed here.

Properties of Seawater Column. For estimating the external force acting on a deep-ocean riser or mining pipe, we should consider two general aspects: One includes the environment characteristics of the local water column, and the other the external force produced by such an environment.

The environment is dominated by the vertical variation of the subsea-current vector, and also seawater properties such as density, viscosity and temperature, along the depth. The subsea-current profile is often three-dimensional (Chung and Felippa, 1980). For mining-pipe-systems or riser-reentry or deployment operations with free-end boundary condition of the pipe, however, the current velocity profile in the operation area, which is not likely unidirectional in the water column, and the ship velocity must be accounted for in the calculation of relative velocities for the pipe system.

External Static Forces and Current Vector. The resultant force of a pipe segment consists of three force components; the forces caused by gravity, external pipe-fluid relative velocity and internal fluid flow, respectively (Chung and Felippa, 1981):

\[
\mathbf{F}(z) = \mathbf{F}_0 + \mathbf{F}_C + \mathbf{F}_I
\]  

Pseudo-Random Modeling of Wave Spectrum. The free surface waves are modeled by a unidirectional wave field, with the free-surface displacement \( \xi(x, y, t) \) taken as a stationary random process (in space and time) that is characterized by a power spectral density \( S_{\xi}(\omega) \). An explicit time-dependent representation of wave elevation and velocity must be generated for a time-domain or transient-response analysis. The wave field may be modeled as a sum of sinusoidal waves:

\[
\xi(x, y, t) = \sum a_n \cos(k_n x \cos \beta_n + k_n y \sin \beta_n - \omega_n t + \varepsilon_n)
\]

where \( a_n \) are the wave amplitudes, \( \beta_n \) is the wave propagation direction, and the wave numbers \( k_n \) and wave frequencies \( \omega_n \) are related by the dispersion relationship for infinite water depth. The phase angles \( \varepsilon_n \) are randomly distributed over \((0, 2\pi)\).
(A) Non-zero Crossflow. For the turbulent flows (Re ≥ 2.5×10^6), the tangential force per element length is established as:

\[
F_t = -\frac{\pi}{2}\rho_d d C_f V \nu V_{RT}
\]

where \(C_f = f(Re, \text{yaw angle})\), \(d = \text{outer diameter of the pipe}\), and \(V_{RT} = \text{tangential component of } V_k\).

(B) Zero Crossflow. When the ship and pipe are heaving in waves with no steady current, the pipe velocity is essentially parallel to the pipe axis: the fluid damping is dominated by the skin friction. Tangential force per element length is:

\[
F_t = -\frac{\pi}{2}\rho_d d C_f V \omega
\]

where \(C_f = \text{friction coefficient} = f(Re, \text{yaw angle})\), \(d = \text{outer diameter of the pipe}\), and \(V_{RT} = \omega = \text{seawater viscosity}\).

**Tangential External Force from Internal Slurry Flow and Pipe Responses.** The tangential force per pipe element length due to the wall friction from the flow of (nodule or crust piece) solid-water slurry can be modeled as (Chung, Huttelmaier and Cheng, 1994):

\[
F_n = \left(\frac{\pi}{4}\rho_d d^2\right) \frac{dp}{dz} s
\]

where \(dp/dz = \text{pressure gradient} = (f/d)\mu V^2 \), \(d_i = \text{inner diameter of the pipe}\), \(f = \text{slurry friction factor} \), \(f = \text{friction factor}\), \(V_i = \text{the slurry velocity}\), \(\rho_i = \text{the slurry density}\), and \(\rho_w = \text{seawater density}\).

Although there are very few published reports, the internal nodule-water slurry was studied by some consortia. The important parameters are optimum concentration of nodules or crust pieces in the slurry, friction factor, wear, etc.

For an 18,000-ft pipe with its bottom end free and a 4,000-ft pipe with its bottom at the seafloor, tangential axial shear forces due to the wall friction from the internal flows of crust-water slurry (Cheng, Chung and Huttelmaier, 1994; Chung, Cheng and Huttelmaier, 1994) are shown to change the pipe responses. For a upward flow velocity of 10 ft/s (3.05 m/s), for example. Fig. 15 shows that the effect increases the displacements in both the x- and y-directions, while it reduces the axial stress slightly. The displacement amplitudes do not differ appreciably from those of zero internal flow.

**Lift Pipe**

Flow-induced Torsional Moment and Pipe Twist. Power or data cables are installed along the pipe, and some pump systems are installed off-center of the pipe. For the airlift, compressed air supply tubes run deep along the pipe. These asymmetric arrangements cause external flow-induced torsional moment.

So far, pipe twisting and lateral pipe deflection have never been considered. Flow-induced torsional moment for ocean mining pipes is of concern, because of potential pipe detorquing and twisting during the at-sea operations (Chung and Whitney, 1993). It was one of the postulated causes for potential detorquing for the heavy lift pipe in the deep-ocean mining operations in the Pacific Ocean. Flow-induced torsional moment, which was noticed in the '70's, were first reported by Chung and Whitney (1993). Pipe twist at the level of the pipe bottom end is in the order of 0.1 rad and 0.5 rad at bottom for 4,000-ft pipe and 18,000-ft pipe, respectively, for the straight-down, 2-cable configuration when asymmetric to the flow direction (Chung, Huttelmaier, Cheng, 1994; Cheng, Chung and Huttelmaier, 1994). The twist must also be known to determine the equipment orientation near the seafloor and may become an important parameter in the pipe thread design. The twist angle is not linear with depth (Fig. 13).

**Fig. 15 Effect of the upward, internal nodule-water slurry flows on the 3-D coupled pipe displacements in the x direction at node 19 (bottom) to the motion with the horizontal and axial oscillation amplitudes, \(x_c = 5\) ft and \(z_c = 3\) ft, respectively, excited at \(T = 5\) s, when \(V_c \neq 0\) profile and (MT)\(x \neq 0\) and (MT)\(y \neq 0\)**

One surprising result for the asymmetric configurations of the straight-cable models is the nonzero mean lift (or lateral force), which can push the pipe in the lateral direction (Chung and Whitney, 1993). Depending upon the current velocity, the lateral pipe motion velocity and the associated lift, the lateral pipe oscillation can also be induced when operating beyond a certain pipe velocity. When the straight-down-cable configuration is used, maintaining symmetric orientation or configuration of the pipe system during its deployment or ore lifting operations would be extremely difficult or practical, and the current velocity along the water column of the deep ocean can vary in both direction and magnitude.

**Pipe Strength, Joint and Cables.** The international consortia have used prototype pipes during the at-sea tests, although the details have not been fully published. Japan's program (Ishikawa, Morikawa and Ohta, 1992) selected a high-tensile steel and threaded joint. It looked mainly at the strength design, while OMCO (Chung, Whitney and Loden, 1981) was more concerned with the dynamic behavior of the pipe bottom end. The difference in emphasis may be due to the difference in their respective mining systems for the integrated control. For the OMCO system, the key elements in the integrated system control are to predict accurately and control pipe/buffer motions to enable efficient mining operations (Brink and Chung, 1981). A buffer is a large mass at the bottom end of the pipe. Vortex shedding also introduces control problems, as well as restrictions, on heading and speed, which can be alleviated by use of vortex-shedding suppression devices (Chung, Whitney, Lezius, and Conti, 1994).

**SEAFLOOR SWEEP EFFICIENCY**

The commercial production phase should achieve high sweep efficiency (Chung, 1985). Mining efficiency is a function of the efficiencies of individual subsystems of a mining system. One of the most important parameters for an efficient mining system is the seafloor nodule or crust sweep efficiency. This efficiency is a function of the track-keeping ability of the miner to sweep according to the track-keeping control to increase the collection rate per sweep area. Exploration provides data for the local variation in abundance (Fig. 16). The collection rate depends upon the size and efficiency of the miner and collector system. The track-keeping ability can vary considerably according to individual miner systems.
For the nodule collection, some consortia have tested at sea their individual, test mining systems of various depths. The following discussions apply to both nodule and crust mining by tow-sled (TS) systems, CLB systems, or remotely-controlled miner (RCM) systems. The track-keeping ability of the nodule collector of the TS system is directly subject to the steady-state, as well as dynamic, bottom end motion of the pipe (directly attached to the collector), for which the only collector positioning is usually done through the ship positioning control. Also, the CLB system is subject to similar constraints. It appears that these two systems were controlled only through the ship positioning control. The laterally oscillating motions of the pipe can significantly reduce the nodule sweep efficiency of these two systems.

One of the advantages of the RCM system having the pipe bottom end "free", the link system between the buffer and the miner, and a self-propelled miner is to achieve high sweep efficiency, leaving the least amount of uncovered nodules in a given area and minimizing miner downtime. High efficiency can be achieved by leaving the self-propelled miner free to move or sweep the track according to the seafloor track-keeping plan. This frees the miner from the dynamic motion of the pipe bottom end and ensures higher nodule recovery within a given seafloor surface area. One potential disadvantage of the RCM system could be its complex mechanical and control system, as compared to the other two simpler systems. Once the sweep efficiency parameters are properly identified, design of a miner and overall systems can be further improved.

RECENT ACTIVITIES

Presently, only Japan and India are active in the ocean mining program. Finland (Palle; 1988; Pakarinen, 1988) was developing a nodule mining system in cooperation with the USSR, but their activities are on hold. Another international cooperative activity on the development of a nodule mining system between France and Germany in the late '80's (Bath, 1989; Amann, 1991) has also been on hold since the early '90's.

Japan's Program. The Japanese government has promoted the research and development of a nodule mining system by a contract with Technology Research Association of Ocean Mineral Resources Mining System (TRAM) since 1981. They are planning to conduct an at-sea mining test in the Pacific in 1997. The system is composed of a towed collector, a lift pipe system, an airlift system, a pump lift system, an onboard handling system, an instrumentation and control system, and a test mining ship, as shown in Fig. 17. Japan has been developing a system and subsystem components since 1981.

The 13-m long collector will be towed by a flexible hose made of hard rubber, collecting nodules with waterjet flow based on the Coanda effect, separating seafloor sediment, crushing nodules to desirable size distribution, and feeding them into the lift pipe. This phase is almost completed, except for some instrumentation devices, as shown in Fig. 18. The several 1000-m long and 15-cm diameter lift pipe system is also completed with several 100-m long flexible hose. For the airlift system, two of the 3-stage air compressors and air hose are completed. The two 8-stage, deep-submerged pumps and electrical motors have been developed. For the instrumentation and control system, a hybrid, deepsea cable has been developed. This cable is composed of 3 large capacity power cables for the underwater pump, 3 conductor cables for power supply to the instrumentation, and several optical fiber cables for the...
instrumentation and control signal. Deepsea connectors for the electrical power and optical signal have also been developed. Many engineering analyses and simulations have been carried out for: maneuverability of the mining ship with the lift pipe and a towed collector, the collector touchdown on the seafloor, the behavior and stress analysis of the lift pipe, two-phase (solid-liquid) flows for the pump-lift system, three-phase (air-liquid-solid) flows for the airlift system, etc. Construction of the onboard handling system and conversion of the semisubmersible vessel into a test mining ship are the final phase to be carried out for the deep-ocean mining test in 1997.

India’s Program. India has undertaken 44 research cruises in the Central Indian Ocean for the exploration of manganese nodules. For this purpose, 2 Indian research ships (Gaveshani and Sagara Kanya) and 4 ships chartered from other countries were used. Several sampling equipment including grabs, corers and dredges were used, along with echo sounding and seafloor photography. This was enhanced with multibeam surveys since 1989. The resource potential was estimated on the basis of these data. In 1987 India claimed an area of 150,000 km² in the international water under the Law of the Sea. Further surveys are now being conducted (Sharma, 1993).

India projects a semi-industrialized phase by 1997 with a view of commercial nodule mining by 2010 (Yates, 1990). From technological point of view including the nodule processing, however, 1997 for the semi-industrialized phase seems to be overly optimistic. The commercial production depends on the outcome of the previous phase. A mining system concept appeared to be unique in reducing the ocean-surface environmental impact. The system was composed of self-propelled miner, buffer storage and mechanical lift system. The currently favored concept appears to be a hydraulic lift system with a self-powered, crawler-type collector head with nodule-washing and crushing capability. The nodules in a form of slurry will then be lifted by submerged pumps in series to the surface ship through a 5,000 m pipe via a buffer storage. The surface ship of about 70 – 100,000 t is dynamically positioned. Their current activities are research and development on design parameters, model tests of various subsystems in a towing tank and in the coastal water, and development of remotely operated miner and lift systems (Sharma, 1993).

Role of Deep-Ocean Submersible

Manned submersibles for operations at water depth in the range of 6,000 m were desirable, but were not available for the exploration and at-sea mining system tests in the ’70’s. Despite the rapid advancement in the acoustics, image processing, and fiber optic cable, the manned submersibles are still valuable equipment to support the deep-ocean research.

The manned, deep-ocean dive can provide valuable support services and data: direct observation of the seafloor operation and control and nodule/crust, nodule and crust sampling, in-situ geotechnical data and core sampling, seafloor miner, underwater equipment operations, monitoring, inspection, repair, acoustic signal studies, and various oceanographic services. The 5 submersibles that can dive to 6,000 m are: America’s Sea Cliff (1983 refit), France’s Nautile (1985), Russia’s Mir I and Mir II (1987) constructed by Rauma-Repola (Finland), and Japan’s Shinkai 6500 (1990).

BENEFIT TO DEEP-OCEAN RESEARCH

Nodule and crust mining from 800~6,000 m seafloor will bring in many new complex problems which would require subsequent technology development for the design, as well as the operation, of the mining systems. Deep-ocean drilling, pipe-laying, survey, tow cable, and deepsea scientific research will all benefit from the new technologies evolving from deep-ocean mining. One clear benefit to other deep-ocean research is equipment design for very high hydrostatic pressure.

Data for miner design and operation are related to deep-ocean subsea and equipment design technology. Pipe technology is directly related to the deep-ocean riser, pipeline, J-pilelaying, and cable design. The importance of axial pipe stress in design (Chung and Whitney, 1981) was recognized in the riser design. The important role of seawater viscosity variation along the depth in the pipe drag has been used in offshore design (Chung, Whitney, and Loden, 1981).

Examples of larger ship thrust and set-point management unique in deep-ocean mining are given as follows: Drag when towing the very long pipe becomes a significant portion of the thrust power of a mining ship. Physical environment changes along the water column greatly influence the dynamic positioning control of the entire mining system. This results in the variation of the force distributed along the pipe. Subsequently, such parameters could leave some uncertainties in the estimates of the pipe motion and of the total thrust power, thereby affecting the associated system control operations (Brink and Chung, 1981; Chung and Felippa, 1981). Furthermore, the position control of the mining system is more complex than drilling, requiring moving set-point management. The mining system (ship-pipe-miner) has to be controlled to track-keep along a preplanned mining path, while the drilling ship maneuvers about a stationary point. This places stringent requirements on the accuracy in the integrated control operations of the ship, pipe, and miner at the seafloor.

CONCLUDING REMARKS

For a nodule mining venture to be economical, a fleet of mining ship systems should be able to collect enormous quantities of nodules continuously over a long period of time. Currently, technology for some subsystems exists for small-scale test mining. However, the existing mining technology has not yet been applied or proven adequate for commercial production operations. At this writing, no one has tested a commercial production system at sea. International consortia are expected to be formed for investment in joint research, due to enormous cost in developing and testing mining systems.

Before commercial mining operations of manganese nodules take place in the future, a more sophisticated, third-generation technology is expected to emerge. As advances are made, particularly in high technology applicable to individual subsystems, basic design will be updated and future mining systems fully reevaluated. New experts need to be trained to replace the previous experienced experts, nearly all of whom have left the industry or retired. It would be desirable to develop an expert system to gain knowledge from those experienced experts.

For crust mining, more surveys will be required at various locations in the Pacific for its distribution, abundance, and physical characteristics. The technical challenges need to be defined, and crust characterization and engineering data are needed prior to the development of mining system concepts. There are no definite crust mining system concepts.

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