Advances in Manganese Nodule Mining Technology

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ABSTRACT

Technology for mining manganese nodules from the deep seafloor has been reviewed from a research and development point of view instead of from a hardware technology standpoint. Nodule collectors, hoisting systems, and dynamics and remote control are individually reviewed, and systems integration is discussed. The paper concludes with discussion of the importance of systems integration and sweep efficiency.

For commercial mining operations of manganese nodules to take place in the future, a more sophisticated, unmanned, third generation technology is expected to emerge. As technological advances applicable to individual subsystems occur, current basic designs should be updated and future mining systems reevaluated.

INTRODUCTION

The deep seabed is one of the most potentially rewarding frontiers that challenges mankind in its quest for knowledge and material achievement. Resources of the deep seabed promise to make an enormous contribution to the world’s resource base once their potential is fully realized. Presently, one resource of economic interest is manganese nodules, which are spread over the surface of the deep ocean floor at depths of 3,000-6,000 m. But a question must be answered: Is commercial development technically and economically feasible?

Over the last twenty years several groups of companies and government enterprises have invested nearly half a billion dollars in exploring deep ocean hard minerals—manganese nodules in particular—and in researching and developing 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 mining these minerals on a commercial scale. For a nodule mining venture to be economic, a fleet of mining ship systems should be able to collect enormous quantities of nodules continuously for a long period of time.

Some twenty years ago when research and development precipitated manganese nodule mining technology, pioneers found they were faced with a formidable task. Manganese nodules (Figure 1) containing economically attractive quantities of nickel, copper, cobalt, manganese (and possibly 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, hundreds of miles from shore. More recent commercial interest has been centered near the equatorial zone in the North Pacific Ocean. The terrain of the ocean floor, from which the miner or collector scoops nodules, is uneven, abounding in hills, ridges, troughs, rocks, and similar

Figure 1. Manganese nodules from the North Pacific Ocean.
obstacles (Figure 2). In addition, the operations of mining ships and underwater equipment are always affected by waves, ocean swells, and currents. Underwater mining systems are further subject to the subsequent dynamic behavior of the hoisting pipe in response to varying current velocity along the depth. Designers and operators must be sensitive to such parameters for the effective operation of seafloor nodule collectors (or miners).

Active research has been conducted by the industrial consortia for the last 15 years, including at-sea test mining with sled mining systems to check out both mining systems and concepts. Today, design concepts of technology have been refined, small-scale pilot tests and component tests have been conducted in the deep ocean, and technical feasibility has been established. However, information available in the public domain about these efforts has been scarce. The earliest research and development has been conducted by four multinational consortia composed of companies from the United States, Canada, the United Kingdom, the Federal Republic of Germany, Belgium, the Netherlands, Italy, Japan, and two groups of private companies and public agencies from France and Japan, and two groups of private companies and public agencies from France and Japan. Three publicly sponsored entities from USSR, India, and China are also known to have interest in nodule mining.

Manganese nodule mining usually involves coordination or integration of five distinct systems of operations: exploration survey, nodule collection from the seafloor, hoisting to the mining ship, transportation to land, and processing (or processing at sea). This discussion deals with only the second, third, and fourth stages, which are of more interest to offshore (mining systems) engineers.

NODULE COLLECTOR (OR MINER)

Each ocean mining consortium has been developing different concept systems of unmanned, seafloor nodule collectors or miners:

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

The first two are traditional systems, simpler and mechanically more reliable, but lower in sweep efficiency than the last two, primarily because of difficulties in miner track-keeping. The CLB system, which is similar to the traditional land-mining system, may not meet commercial, target production rates. And, while one tow-sled system appears to attempt to increase sweep efficiency by controlling the sled, it seems to the author that the large force on and the dynamic response of the pipe would make it very difficult to control, at the sled level, the dynamic influence of the pipe on the sled. Consequently, sweep efficiency may not be improved. A scale-model of the third system, the shuttle system, was tested by a French consortium. It avoided use of a hoisting pipe, using instead a self-propelled, shuttle miner system with batteries as the power source. Presumably, the consortium anticipates improved battery technology in the future. The RCM system, one of the systems developed by the Ocean Minerals Company, appears to use the most modern technology.

One remote controlled miner system (Figures 2 and 3) proposes a fully automatic position control through sensor feedback information with manual override option. An integrated system of the ship's 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 mining equipment, the ship can be controlled to station-keep over a fixed point on the seafloor. And, during normal mining 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 follows precise mining tracks. More

Figure 2. An artist's sketch of mining equipment (Buffer, Top and Self-Propelled Miner Maneuvering on the Seafloor near a Large Obstacle).
Figure 3. Schematic of a preliminary mining system, remotely controlled and self-propelled. Notations: \( (X,Y,Z) \) is a space coordinate; \( (X_s, Y_s, Z_s) \) the ship coordinate; \( V_s \) the ship or miner velocity; and \( V_c \) the relative pipe tow velocity.

Figure 4. Glomar Explorer, ocean mining ship operated in the North Pacific Ocean.

Figure 5. Nodule lift performance as a function of pipe diameter for hydraulic transport and pneumatic transport.

The nodules collected by the self-propelled miner are in a form of a mixture of nodules, soil particles and subsea water. The buffer is connected at the free bottom end 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.

**NODULE HOIST TO THE SHIP**

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The nodule-water mixtures can be transported by one of the three hoisting pipe systems: either a hydraulic system, or a pneumatic system, or a mechanical system. The hydraulic system hoists or vertically transports the nodules in two-phase (nodule-water) flows by various means (e.g., pumps in series) to the ship through the miner-to-buffer linkage, and up the 5,000 m long, nearly vertical pipe string. If a pneumatic (or air-lift) system is used, the nodule transport involves three-phase (nodule-water-air) fluid flows with air bubbles being released at a certain level of the pipe. The mechanical system includes devices such as the CLB system, which provides good reliability but is considered incapable of meeting commercial daily production rates.

The pneumatic system is considered to be simpler, but would consume more power than the hydraulic system. In order for the pneumatic system to be efficient, the pipe diameter would have to be larger than the hydraulic system: a relative cost can be found in Figure 5. For either case, the mixture ratio of nodules in the hoist system needs to be controlled for optimum transport efficiency and to avoid some nodule flow plugging. For the optimum efficiency of vertical nodule transport through the pipe, the mixture con-
Control can be done by such means as buffer, mining speed, etc., for a given nodule distribution per area. The shuttle system of collection has the advantage of having the capability of transporting the nodules built into the system since it is self-propelled, and therefore, has no need of a hoisting pipe.

**DYNAMIC SYSTEMS AND CONTROL**

One of the relatively new technologies in ocean mining is dynamics and systems control.** The industry recognized early that all traditional branches of mechanical engineering, offshore mechanics, and naval architecture are needed together to solve complex ocean mining problems. These problems have been handled by interdisciplinary approaches, or combined approaches, through interactive treatment of hydrodynamics, structural or solid mechanics, dynamics, and control. Furthermore, the five systems of operations, 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 nodule sweeping efficiency. The pipe response behavior is coupled with, or greatly influenced by, the dynamic behavior and control of the ship and buffer, and by the variation of the subsurface physical environment such as current velocity varying in both direction and speed (Figure 6). 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.

**SEAFLOOR SWEEP EFFICIENCY**

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 sweep efficiency. This efficiency is a function of the track-keeping ability of the miner (or nodule collector) to sweep according to the track plan of the nodule collection rate per sweep area, and of nodule abundance. Exploration can provide the local variation in nodule abundance (Figure 7). The nodule collection rate depends upon the design and operation of the collector systems. The track-keeping ability can vary considerably according to individual miner systems.

Consortia have also tested at sea their individual, small-size test mining systems of various depths. They include tow-sled (TS) systems, CLB systems, and 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 can be controlled only through the ship positioning control. The non-straight or oscillatory motions of the pipe could significantly reduce the seafloor or nodule sweep efficiency of these two systems.

One of the advantages of the RCM system having the pipe bottom end "free," the linkage between the buffer and the miner, and a self-propelled miner is to achieve high nodule sweep efficiency, leaving the least amount of unrecovered nodules in a given area. High efficiency can be achieved by leaving the self-

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*Note: The image contains a page number (42) and a journal reference (MTS Journal • Vol. 19, No. 4).*
propelled miner free to move or sweep the nodule track according to the seafloor mining 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 (or collector) and overall systems can be further improved.

DEEPWATER DRILLING COMPARISON

Nodule mining is conducted at greater depths and requires a much larger ship than deepwater drilling. This brings in many new complex problems which would require subsequent technology development for the design as well as the operation of the mining systems. One such example is equipment design for the magnitude of hydrostatic pressure at such depth. A few considerations are outlined below.

Because of the pipe length, the drag force to tow the pipe can become a significant portion of the thrust power of a mining ship. This in turn influences the dynamic positioning control of the entire mining system. The subsurface environment and the current velocity profile, in particular, vary a great deal—both seasonally and daily along the depths of the Clipper-ton and Clarion regions. Variation of sea water viscosity near the equatorial area of the Pacific Ocean should also be considered. This results in variation of the force distributed along the pipe. Subsequently, such parameters could leave some uncertainties in the estimates of the static and dynamic pipe motion and of the total thrust power, thereby affecting the associated system control operations. Furthermore, the position control of the mining system is more sophisticated than that for offshore drilling systems, even for the same water depth. The mining system (ship-pipe-miner) has to be controlled to move continuously (or track-keep) along a planned mining path, while the offshore drilling ship maneuvers about a stationary point (the well). This places stringent re-

Figure 6. Interrelationship among environmental, hydrodynamic, and structural models.

Figure 7. An example of nodule abundance and topography—25×25 NM.
quirements on the accuracy of the coordination needed for control operations of the ship, pipe, and miner at the sea floor.

CONCLUDING REMARKS

Currently, technology for some subsystems exists for small-scale test mining. However, this mining technology has not yet been applied or proven adequate for commercial production operations. Efficiency and reliability obtained at the development and testing stages are usually proprietary.

For commercial mining operations of manganese nodules to take place in the future, a more sophisticated, unmanned, third generation technology is expected to emerge. As advances are made, particularly in high technology applicable to individual subsystems, basic designs should be updated and future mining systems fully reevaluated.

REFERENCES