ABSTRACT

The review is an update from the review presented at the OMS-2005 (Chung, 2005). It includes discussions on the technical issues that have been already identified in the literature for manganese nodule production system design and on initial stages of crust mining concepts. It appears no new additional issues have yet been identified and solved. Recent discovery of the buried nodules would necessitate a new miner/collector concept. Under the present step-by-step water-depth approach the realization of a cost-effective commercial deep-ocean mining system will take much longer than is claimed or targeted. The present incremental (step-by-step) approaches for not much deeper than 100 m in equipment design and testing in the coastal water for past 10 to 15 years may be worth re-assessing against a direct approach for 5,000-m depth technology and system development.

KEY WORDS: Deep-Ocean, mining, manganese nodules, crusts, Hughes Glomar Explorer, full-scale tests, sea-floor vehicle, pipe, riser, integrated system.

* The statements in this paper is the author’s, not ISOPE.

INTRODUCTION

The recent state of technological developments in the countries that have joined deep-ocean mining since the ’90s is reviewed in terms of readiness for the development of a commercial mining technology. The recent developments are funded primarily by their respective governments at small budget scales. This review uses as baseline the previous large-scale international R&D work performed in the 70’s on 5,000-m, deep-ocean mining technology and systems.

Previous Developments

The design of the Hughes Glomar Explorer (Fig. 1) was one of the greatest technological innovations in ship and deep-ocean technology of the century. The Explorer, with its deep-ocean mining system, had a huge rectangular door, the so-called moon pool: 270 ft (82 m) long, 70 ft (21 m) wide in the bottom of the ship hull, this could be opened and closed in mid-ocean. A large, remotely controlled, self-propelled ocean-floor miner with a 5,000-m-long steel pipe system—OD 15-in (38-cm); ID 7.5-in (19-cm)—deployed and retrieved through the moon pool’s open door for operation on the nearly 6,000-m-deep ocean floor (Fig. 2). Its pipe handling and deployment of the 5,000-m-long pipe were automated. Even now, no new systems have been developed that can match the capability of the Explorer’s heavy lift system, heave compensator and large, remotely-controlled, self-propelled miner (ocean-floor vehicle),
which operated on the 5,000-m-deep ocean floor of the North Pacific in 1976 and 1979 (Chung, 2009a and 2009b).

In the '70s, the U.S.-based international consortia carried out their R&D programs as private enterprises and claimed their respective manganese nodule areas in the Pacific Ocean. The greater part of the development of the deep-ocean mining technologies and systems for exploration, nodule recovery and processing took place in the '70s. Most of the claims of deep-ocean mining R&D by the international consortia are made orally, and very limited, specific, documented proof was made available in the public domain.

DEEP-OCEAN MINING SYSTEM TESTED WITH HUGHES GLOMAR EXPLORER IN PACIFIC

Commercial Deep-Ocean Mining System Developments (Chung, 2009a)

The Lockheed–Dutch Shell-Amoco–Bos Khalis Consortium, called the Ocean Minerals Company (OMCO), was formed in 1975. This consortium was the deep-ocean mining systems and technology developer and was led by the Lockheed team. As a step toward developing a third-generation commercial system and technology (Fig. 3), OMCO developed a second-generation large-scale deep-ocean test mining system and tested it with the Hughes Glomar Explorer (Fig. 1) by conducting 2 at-sea tests in the North Pacific in 1976 and 1979 (Figs. 1 and 2). The deep-ocean test mining system as tested consisted of an integrated ship–pipe–buffer–flexible-miner (self-propelling on the ocean floor) and control link (Figs. 2 and 3). A typical strip-chart recording (Fig. 4) shows the motions of the Explorer coupled with the 5,000-m heavy-lift pipe with the miner on the bottom of the North Pacific (Chung, 2009a); the associated large-amplitude axial pipe oscillation at its resonance (Fig. 5) confirmed the theoretical prediction by Chung and Whitney (1981).

Further, the OMCO team (Brink and Chung, 1981; Chung, Whitney and Loden, 1980) developed a third-generation commercial and totally integrated system (TIS); the control of the ship-pipe-buffer-link-miner and supporting technology, as well as the design and control operation of a system (similar to Fig. 3) with the 300,000-ton ship in a 5,846-m-deep ocean, was simulated (similar to Fig. 3). This dynamics and control of the integrated system software came from modular design. The latter made it much easier and very fast to modify the subsystems module and to simulate the entire system for integration of system design changes.

Who Did What in '80s and '90s?

After OMCO's at-sea test with the Hughes Glomar Explorer in 1976 and 1979 and its development of a commercial integrated system, and after the tests by 3 other consortia, Japan started its national program of deep-ocean nodule mining in 1981 (Chung and Tsurusaki, 1994). However, it conducted only a scaled-down at-sea test of a tow-sled collector component without a pipe in late 1990.

Following the U.N. Law of the Sea that became effective in 1995, the U.N. “pioneer investors” (or “contractors”) are represented by their governments or designated organizations, filing the claims of their manganese nodule areas in the Pacific Ocean. The R&D for the mining systems’ development and technology by India, China and Korea is of a small scale and still in the very early stage.

There has been little breakthrough in technology since 1980. The present incremental (step-by-step) approaches, which have gone on for the past 10 to 15 years and whose equipment design and testing in coastal water is not much deeper than 100 m, may be worth re-assessing against a direct approach for a 5,000-m-depth technology and system development.
Another fundamental question: Under the present incremental approach, from shallow to deep, then deeper, then yet deeper—when can the systems for 5,000 m be developed? Can the present and planned test data be scaled up to a 5,000-m system?

INTEGRATED MINING SYSTEM MODEL

Recent concepts that have come to be preferred by many countries are basically OMCO’s concepts of the 70s (Brink and Chung, 1981; Chung, 1985; Chung, 1996; Chung, 2009a). The main features of OMCO’s remote-controlled miner as combined miner and collector (Fig. 2) are the integration of the self-propelled, remote-controlled ocean-floor miner (RCM) with the free bottom-end of the pipe, the miner-to-buffer link, a buffer at the pipe’s bottom end, and the ocean surface system as a nearly totally integrated system control.

The Total Integrated System (TIS) (Fig. 4) (Park, Min and Chung, 1997) is a version upgraded from OMCO’s controlled miner: This is an integration of subsystems of manganese nodule production or mining from the ocean floor, transport to the ocean surface, transport to the land base, and processing on land, onshore or in the ocean. The ocean-floor disturbance by the moving collector discharge and miner can be a major component of environmental issues, followed by sediment cleaning near the ocean floor, and discharge from the ocean surface (Chung, Schriever, Sharma and Yamazaki, 2002).

The present review is based on this TIS model, as it was OMCO’s TIS (Brink and Chung, 1981) that used the most advanced technologies of the time among the international consortia. The tow sled and the collectors (Chung and Tsurusaki, 1994) were one of the basic systems for the consortia other than OMCO in the 70s and for Japan in the 80s up through to the 90s.

OCEAN SURFACE SYSTEM

Ship System and Dynamic Positioning

According to Brink and Chung (1981), the following are givens for a commercial system development:

1. The control system and computer simulation of the integrated ship, pipe, pipe-handling, buffer and ocean-floor miner made possible the speedy change of subsystem module concept tests and integrated system design and performance for production operation.

2. The efficient, nonconventional maneuvering capability, such as a ship’s so-called crabbing, reduces downtime, minimizes thruster power consumption, and achieves higher ocean-floor nodule sweep efficiency by the track-keeping miner on the ocean floor.

3. The decision as to whether to process minerals on land or at sea, and as to what metals are of primary interest, greatly influences ship size, recovered mineral storage, ship system design, and shuttle-ship requirements for transshipment and ocean transport.
4. Pipe design and position control are one of the most critical technical issues. Technological innovation is needed for the rapid deployment and retrieval of the pipe (-buffer-miner) system within the present storm-forecasting capability.

5. The hydrodynamic design of the ship system can be performed adequately with the existing technology.

Significant developments toward a prototype surface system concept have been little.

PIPE/BUFFER SYSTEM

Pipe System for Vertical Transport

For optimum nodule (or solid) lift efficiency, the control of optimum nodule concentration in the nodule-water mixture is desired. This is directly related to the nodule abundance distribution and the miner speed control on the ocean floor, and the associated nodule transport (miner-buffer level and lift through the pipe). The nodule transport requires accurate pressure gradient or friction modeling for pump power for the hydraulic lift and compressor for the pneumatic or air lift. OMCO’s Schick (1980) presented a comparison between hydraulic lift and air lift in terms of pipe diameter and nodule-mixture flow rates in the selection of a lift system for a 4,877-m-deep ocean floor (Fig. 5).

Since the OMCO consortium designed and tested a buffer in the North Pacific Ocean (Fig. 6), sketches of nearly all recent mining systems show buffers similar to OMCO’s, but still no real prototype buffer design concept.

Schick (1980) presented a relative comparison of efficiency and power as a function of the pipe’s inner diameter for the hydraulic and pneumatic lifts for commercial mining development. In the ‘90s and early ’00s, more fundamental studies of nodule-water transport have been conducted. The hydraulic lift has actually been studied the most (Xia et al., 1997), with pipe diameters ranging from 25.4 mm to 150 mm, and flexible pipe length up to 400 m (Deepak et al., 2001).

Non-Newtonian nodule-water flows. A diluted non-toxic polymer solution in the solid-water mixture substantially reduces (by as much as 80%) the drag or pump power (Chung, Yarim and Savasci, 1999).

The model-scale experiment (Chung, Lee, Tischler and Yarim, 2001) revealed that the pressure gradient of the present 100-mesh fine sand particles is higher than the measured Re range, as compared to the larger-mesh sands: This is contrary to the common perception that “the larger the particles, the larger the drag or pressure gradient.”

Effect of nodule surface shape. Chung et al. (1998) presented this result with the 25.4-mm pipe: the larger the concentration of the larger particles, the smaller the effect of particle surface geometry on the pressure gradients. This was evident in Yoon’s experiment (2009) with real-size nodules in 10-cm pipe: The difference in hydraulic gradient between the irregular-shape real manganese nodules and the spherical synthetic manganese nodules is not particularly apparent except at high velocities and high concentrations. However, when the solid volume fraction is high (e.g., 20% volume), the hydraulic gradients of the flow of the real manganese nodules were a little lower than those of the artificial ones.

Pump developments for hydraulic lift. COMRA (Zou, 2007; Yang, 2008) reported fabrication of a 2-stage pump for a 1,000-m-deep test.

New nodule lift concept and concentration measurement. Sobota et al. (2009a) propose a new concept of nodule lift by feeder(s) from the ocean floor. Sobota et al. (2009b) applied a radiometric scanning method to measure the vertical distribution of density (or solid concentration) in a horizontal pipe.

Fig. 7 Two stage lifting pump (Zou, 2007)

Gas hydrate production. Recently Sakamoto et al. (2009) studied field scale simulation on gas production behavior during depressurization process in methane hydrate sediments.

Pneumatic nodule transport. Shimizu et al. (1992) discussed Japan’s airlift experiment with a flow loop of a 200-m-long pipe of 100 mm in diameter. Still, little useful data were presented.

Pipe System for Pipe and Buffer Behavior and Position Control

This is one of the most critical, technically high-risk issues in the deep-ocean mining system development and operation.

The buffer at the pipe’s free bottom-end must be controlled within an allowed envelope of the moving miner during the track-keeping control operations. A full understanding and simulation capability of the dynamic and static, coupled axial, bending and torsional behaviors of the pipe system are essential for designing a TIS (production-control) system and pipe design.

While estimating the vertical clearance between the buffer bottom and the ocean-floor surface in support of the Explorer’s at-sea test, Chung and Whitney (1981) found that the axial stress is the design stress, not the bending for a pipe as long as their 5,846-m pipe. This has been recognized in the industry design since the early ’80s.

Further, after accounting for the torque applied by the external moments on the pipe with cables and the buffer, the static pipe twist can be as large as 0.66 rad (Chung et al., 1994). Some of the key design and operational issues are as follows:

- The position-control pipe-bottom or buffer must stay within an allowed envelope or slant range while performing continuous, precise miner track-keeping operations on the ocean floor.
- Resonance frequency and motion characteristics of the pipe must be avoided.
- Flow- or vortex-induced pipe vibrations must be avoided.
- Axial vibration amplitudes and stresses must be reduced.
• Hydrodynamic damping must be estimated as accurately as possible.

While hydrodynamic damping greatly influences the pipe’s deflection and lateral as well as torsional vibration amplitudes, we do not know the true hydrodynamic damping values along the pipe in the ocean.

The present author’s groups developed the software during 1975-80 for the above simulation and design of an OMCO integrated mining system (Brink and Chung, 1981; Chung, Whitney and Loden, 1980), as well as another software with research grants from the U.S. National Science Foundation (NSF) (1992-2000) (e.g., Cheng and Chung, 1997). The software is a FEM software for the static and transient responses of a pipe for deployment and mining operation in a 5,486-m water depth; axial, bending and torsional deformations are coupled for both softwares.

But progress appears to be seriously lagging behind other subsystem development. No such software as the above, with the coupled axial, bending and torsional deformations and buffer control with pipe dynamics included, is noticed in the literature.

BUFFER-TO-MINER LINK SYSTEM

This link, intended to transport nodule, sediments and water mixtures to the buffer at the bottom of the pipe, is not a strength member, and it is not vertical. Electromechanical cables along the link supply the power to the self-propelled miner and collector. The pipe control, distribution of nodule abundance on the ocean floor, nodule collection rate and miner speed are directly tied to the production control and link size.

China and Korea propose general concepts of flexible links in their experiment or simulation based on the conceptual flexible link. However, there have been no new buffer-flexible link-miner design and tests in the deep ocean since OMCO designed and at-sea tested a buffer-flexible link-miner in the Pacific Ocean (Fig. 2).

NODULE MINER OR COLLECTOR SYSTEM

The mobility, reliability, safety, collection efficiency and sweep efficiency of the miner (or collector) system are the most important parameters in deep-ocean mining system design. The pipe position control affects all of these parameters. Two serious candidates are described below.

1. Self-propelled, Remote-controlled Miner (RCM) System

OMCO developed large-scale self-propelled test miner(s) (Fig. 2) and conducted at-sea track-keeping control tests of an RCM on the 4,877-m-deep ocean floor in 1976 and 1979 in its claim zone in the North Pacific Ocean with the mining ship Explorer (Fig. 1). The RCM’s self-propelled, maneuvering control system operation on the 4,877-m-deep ocean floor was one of the at-sea test tasks.

In 2000, small-scale, self-propelled miners were tested by India in that country’s Tuticorn coast 410 m deep and in Changsha, China. Chung (1999) proposed a smart miner that can be designed with modern control algorithm to track-keep without knowing the precise soil and near-bottom current properties.

2. Tow-Sled (TS) System

The TS system (Chung and Tsurusaki, 1994) is traditional, simpler in design, and can be mechanically more reliable, but it is lower in both mineral-recovery sweep efficiency and mineral recovery rate than the RCM system, primarily because of a lack of pipe-collector’s track-keeping control capability. Such systems were tested at sea by some consortia and others. In 1997 a Japanese collector test was conducted while a ship towed the collector by cable in the 2,200-m-deep ocean (Yamada and Yamazaki, 1998), but no data were presented in the paper.

Crust Miner

Chung (1994) presented a cobalt-rich, crust-mining system concept that uses a self-propelled miner with vibrators to fracture the crusts and lift via a hydraulic system. Liu and Li (2007) proposed a crust miner concept with control simulation of crust mining. One of the technical challenges is to mine the crust on the ocean-floor slope, as often a steep slope has a rich crust deposit.

Smart Miner

New control algorithms allow for the design of a smart miner to track-keep without knowing the precise soil and near-bottom current properties. Learning and adaptive control algorithms can make set point management less difficult. For example, Successive Learning Track-keeping Control (SLTC) is an on-line active control algorithm that can perform such a task. It has the capability to learn (Chung, 1999).

Buried nodules. Kotlinski and Stoyanova (2006, 2007) reported that the data collected from 59 boxcore stations showed massive deposits of buried polymetallic nodule distribution in the eastern Clarion-Clipperton Zone (Fig. 8). The greater part of the location is associated mainly with hills and slopes of the ocean floor. In general, the buried nodules are larger than the surface nodules. The buried nodules will require fresh new miner/collector design concept developments.

No new miner systems appear to have evolved since the ’70s. Most of the recent nodule mining R&D is based on the collection of information previously published or presented by others since the ’70s. Most of the key consortia R&D results of the ’70s have not been made available to the public.

INTEGRATED CONTROL

Control subsystems to be integrated as a total integrated system control (TIS control) are:

• Ship track-keeping positioning control
The level and activities of deep-ocean mining R&D since the '90s are in their very early learning stage relative to the major international R&D activities of the '70s.

• System and technology development for commercialization requires clearly defined guidelines or regulations in the early stage, thus saving substantial time and cost. The commercialization of deep-ocean resources first requires the development of a well-defined TIS control system, technical innovation and cost-effective technology, as well as cost estimates.

• The development of a cost-effective commercial system and specific commercial mining system models (e.g., TIS) should be defined before the start of the subsystem development. Otherwise, another costly and time-consuming learning cycle may repeat, forcing the development of a new system or subsystem all over again.

• Mining buried nodules and crusts requires new miner design concepts.

• There is some progress in the design of a pump up to 1,000-m depth.

• New nodule lift concept and concentration measurement methods are being developed.

• Recently a field-scale simulation was conducted on gas production behavior during the depressurization process in methane hydrate sediments.

• Deep-ocean mining technology is transferable with minor modification to and from deep-ocean petroleum drilling and production. The design, test operations and experiences of deep-ocean mining system(s) conducted in the 5,000-m water-depth range in the '70s instilled some confidence in the then-newcomers.

The present incremental, cautious step-by-step approach taken in the past 10 to 15 years may be worth re-assessing against the direct approach for 5,000-m depth technology and system development of the '70s.

Present offshore petroleum technology benefited a great deal from the previous large-scale international R&D work in the 5,000-m depth. Today’s ocean-mining technology R&D would need a technology transfer from offshore technology. 

REFERENCES


