Manganese Nodules (II): Prospects for Deep Sea Mining

The history of mining is replete with examples of recovery and extraction techniques whose development was stimulated by new ores. The discovery in some parts of the Pacific Ocean of manganese nodules that also contain nickel and copper in higher concentrations than most ores being mined today is having a similar effect. Whether the methods now being developed to dredge nodules from the deep seabed and to extract pure metals from the nodule ore will become the basis of a new mining industry is still uncertain—economic, environmental, and legal questions about the feasibility of deep sea mining remain to be answered. Nonetheless, development of what may prove to be a major new marine technology appears well under way.

The participants include both industrial concerns and governments. Leading the field appear to be several U.S. firms—Howard Hughes' Summa Corporation, Deepsea Ventures, Inc. (a Tenneco subsidiary), and Kennecott Copper Company, all of which are engaged in exploration and the development of mining and processing systems. Others include Ocean Resources, Inc. and the Canadian-based International Nickel Company (INCO). In Japan and Western Europe the national governments have taken an active role in partnership with industrial groups such as the Sumitomo group in Japan, an association headed by Metallgesellschaft AG and Preussag AG in West Germany, and the French Société le Nickel. The Japanese, in combination with Ocean Resources Inc., have actively worked on the development of a mining system, while INCO, the Germans, and the French have so far emphasized exploration and process development.

The potential profits from deep sea mining operations will depend heavily on the metal content of the nodules, their size and abundance on the ocean floor, and the characteristics of the underlying sediments. Consequently, those interested in mining have spent considerable effort in exploring for rich deposits. The principal technique has been to scan the sea floor with an underwater television camera and to collect samples at periodic intervals for later analysis. Typical high grade deposits are reported to assay 27 to 30 percent manganese, 1.1 to 1.4 percent nickel, 1.0 to 1.3 percent copper, and 0.2 to 0.4 percent cobalt (although nodules with higher assays have been found) and to have about 10 kg of nodules per square meter.

The dredging methods now in use are limited to about 300 m, and to recover nodules from deposits at depths of 5000 m or more requires new techniques. Two principal types of deep mining systems are being developed. One, a mechanical system known as the continuous line bucket (CLB), consists of a long loop of cable to which specially designed dredge buckets are attached at intervals of 25 to 50 m. A traction drive (on the mining ship) moves the cable so that buckets descend into the ocean, are dragged across the seabed to scoop up nodules, and return to the surface to deposit their load.

A second, hydraulic recovery method consists of a length of pipe suspended from a mining ship; a sea floor device (dredge head) designed to collect nodules, screen out those larger than a certain size, and feed the rest to the bottom of the pipeline; and some means of pumping water up the pipeline with sufficient velocity (about 4 m/sec) to transport the nodules as well. The bottom device is either self-propelled or dragged across the bottom by the pipe string, depending on the design. Both conventional centrifugal pumps and compressed air injected into the pipe (air-lift pumping, in which the air bubbles provide enough buoyancy to raise the entire column of water and nodules) are being considered.

Mining Nodules Will Not Be Easy

Either system must contend with the difficulties of operating a mining ship in all kinds of weather, of controlling an extremely long length of pipe or cable, and of collecting nodules from a seabed of uncertain and variable physical properties. According to John Mero of Ocean Resources, Inc., the CLB system has the advantage of simplicity and flexibility, since it has no underwater machinery, can recover nodules of any size, and does not need to be designed for a specific depth and type of sediment as do hydraulic systems. Moreover, he claims that the system will cost much less than the more complex hydraulic equipment, although most other marine engineers dispute his estimates.

Mero admits, however, that such measures as shark-proofing the polypropylene cables and using two surface ships instead of one to keep the bucket loop from becoming entangled when the system is shut down may be necessary. A more serious difficulty is that the buckets must actually pick up a good load of nodules but little sediment for the system to be economic, and there is no way to control how the buckets interact with the bottom. Perhaps the most fundamental limitation of the CLB system, according to critics, is that cables are not strong enough and cannot be moved rapidly enough to mine 3 or 4 million tons of nodules per year with a single unit—a capacity that hydraulic systems can achieve and that many companies believe to be the economic minimum.

Hydraulic systems, on the other hand, require more elaborate gear, and a ship specially equipped to handle a long string of pipe. Centrifugal pump systems must be electrically or hydraulically powered underwater, a tricky and trouble-prone arrangement in the marine environment. Air-lift systems, however, are less efficient and must cope with the complexities and potential instabilities of three-phase flow (the pipe will simultaneously contain water, air, and nodules moving together). The bottom device, the key to a successful mining system, must traverse or sweep the loosely compacted sediments of the sea floor without becoming bogged down. Hydraulic systems are limited to recovering only part of the available resource, since larger nodules that might block flow in the pipe must be left behind. And the complete system may be expensive.

The advantages and disadvantages of each system depend in part on who is doing the talking, of course, and in a competitive arena such as deep sea mining, no company will disclose precise details of its own system, so that much of the available information comes from competitors. Claims and counterclaims are therefore to be regarded with some caution.

Experience with both systems is limited. The CLB system was tested in 1970 by an agency of the Japanese government and again in 1972 by a consortium headed by Ocean Resources, Inc. Deepsea Ventures has successfully tested an air-lift hydraulic system in relatively shallow water and plans deep-water tests in 1975. The Hughes organization has built the first full-size prototype of a mining ship (Fig. 1) which is now at sea beginning tests of an elaborate hydraulic system.

The enigmatic Hughes is a relative latecomer to the deep sea mining race, but there is general agreement that he bought the best expertise available and now is well in front. His system was designed by the Lockheed Missiles and Space Company, who have an impressive record of experience with undersea technology, and by Global Marine, Inc., who operate (for the National Science Foundation) the deep sea drilling ship *Glomar Challenger* that has pioneered mid-ocean drilling techniques. Indeed the Hughes mining ship is essentially a more sophisticated version of the *Challenger*.

In addition to the ship, the Hughes system includes a massive bottom device (several versions of which are to be tested on the current cruise). Because the collecting device is too large to be lowered through the pipe-handling well in the ship's hull, it is to be connected to the pipeline underwater from a submersible barge before being lowered to the sea floor. The barge is in essence an undersea launching platform and mining support vehicle. The bottom device may look something like one described in a patent issued to Global Marine, which consists of a collector on a long rotating boom pivoting around a fixed base where the nodules are cleaned and crushed before being pumped up the pipe. In this arrangement, according to marine engineers, the system could sweep out a large area before being repositioned and would avoid the difficulties associated with towing a long pipeline and a dredge head through the water. Several hydraulic pumping systems are also apparently being tested, although some of those working with Hughes are known to believe an air-lift system is the best.

Competitors have a high regard for the capability of the Hughes team. Raymond Kaufman, of Deepsea Ventures, has "no doubt that they'll succeed technically." But Kaufman and

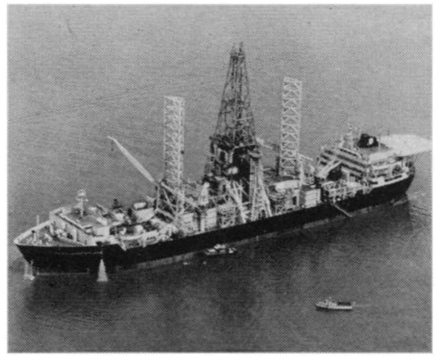

Fig. 1. The Hughes *Glomar Explorer*, a 36,000-ton experimental ship for deep ocean mining. The 200-meter long vessel has a center well and derrick to handle the pipe from which mining equipment will be suspended and sophisticated systems to hold the ship steady and in position during mining. [Source: Summa Corporation]

others believe that the Hughes system may be too elaborate and too expensive to compete. "Lockheed sold Hughes a Cadillac," one engineer put it, and others told *Science* they believe Hughes is more interested in making a name for himself as a pioneer than in making a profit. Both charges are denied by Paul Reeve of Summa Corporation, who asserts that the company has every intention of making a profit.

The hydraulic mining system being developed by Deepsea Ventures, Inc., is more modest than that of Hughes. Their design includes a much smaller collecting device that is essentially a passive dredge head dragged across the ocean floor on the end of a pipeline. Sets of tines much like those on a rake collect the nodules, screen out those that are oversize, and help to separate the nodules from the sediment. An air-lift system is used to bring the nodules to the surface. Because of its simplicity, the system (it involves no underwater pumps or other machinery) has the advantage of low cost and reliability of operation, according to Kaufman. Because of the relatively crude collecting device, however, it must be carefully designed to match sea floor conditions at a particular mine site. And because the dredge must be towed across the bottom without exerting undue stress on the pipeline, the mining area must be very carefully surveyed before mining can begin. The Deepsea Ventures system is thus a less universal mining system than that of Hughes.

Another difference is in capacity. Deepsea Ventures intends to recover about 1 million tons of nodules per year, whereas the Hughes team is known to be aiming for 3 to 4 million tons a year or more. The difference is related to the metals which are the ultimate aim of the mining efforts. Hughes, along with Kennecott, INCO, and apparently many others interested in deep sea mining, believes that copper and nickel will be the prime metals obtained from the nodules. To obtain enough of these metals for profitable operation, large tonnages of nodules are needed. Deepsea Ventures, on the other hand, is planning to extract and sell manganese and cobalt as well, rather than consign them to the scrap heap. Because there is so much manganese in the nodules, fewer are needed to yield a marketable amount of metals. The decision to include manganese influences not only the design of Deepsea Ventures' mining and processing system but also the company's business strategy, since they must find new markets (in the steel industry, for example) for manganese metal.

Most other companies are waiting to see what Hughes is doing and whether he is successful before committing themselves to mining systems. Kennecott, for example, is known to be designing a hydraulic system, but is moving very slowly. The Germans have published research on hydraulic mining designs, but are not far along in developing a system. The syndicate of companies which owns the rights to the CLB system will probably raise the money for a final test of that technique in the next couple of years, according to Mero, but no definite plans exist. INCO is maintaining an interest in both types of systems but has made no commitment to either.

Work on methods of processing the nodule ore is much further advanced. Kennecott has operated several pilot plants and is proceeding with the design of a full-scale system. Deepsea Ventures is nearly as far along. European companies, especially in Germany, have large research efforts on processing under way. Since a processing plant is expected to account for more than half of the cost of a complete nodule-mining operation, the stakes in choosing the best extractive method are high and four or five processes are being investigated.

Straightforward methods of extracting metals do not work because of the nature of the nodules. The manganese oxide and iron oxide minerals that are the main metal constituents of the nodules are extremely fine-grained. Consequently, physical means of separating the metals have not proved successful. Smelting the nodule ore has been tried, also without great success. Although it is possible to reduce the oxides by heating in a furnace to a temperature of about 1500°C, the result is an alloy of various metals (including iron) that is difficult to separate further. In consequence, chemical (hydrometailurgical) separation methods seem to be of most interest to the industry.

In the chemical approach, the nodules are partially or completely dissolved and the metals separated from solution. The task is made easier for those who seek to recover only nickel and copper, since these metals are predominantly found in association with the manganese minerals (adsorbed onto them or embedded in the crystal lattice). Cobalt is found mostly in the iron. Hence several different reagents, selective leaching techniques, and reducing treatments can be utilized, depending on the desired product.

Several investigators have tried leaching the nodule material with sulfuric acid. The acid readily dissolves the copper, nickel, and cobalt, but also some manganese, iron, and undesirable trace elements. Large quantities of acid are required, presumably due to the presence of basic material trapped in the nodule. The consensus is that the technique is not selective enough for commercial use.

A second selective leaching procedure is based on ammonia in conjunction with an ammonium salt (ammoniacal solution). First the oxide compounds are reduced to a lower oxidation state by roasting with a gaseous reagent such as carbon monoxide. Then the ore is treated with ammoniacal solution, sometimes under conditions of increased temperature and pressure. According to D. W. Fuerstenau of the University of California at Berkeley, this process can dissolve more than 80 percent of the copper and nickel and about 50 percent of the cobalt, leaving the manganese and iron essentially intact. The process is similar to one used to extract nickel from laterite ores. Kennecott has obtained several patents for ammoniacal leach processes and is believed to be basing its commercial plans on a version of this method.

A third process involves dissolving the entire nodule. The ore is roasted with sulfur dioxide to reduce the oxides and then leached with water. The resulting sulfate salts are separated to obtain the metals (a tricky process about which little has been published). Alternately, sulfur dioxide in water is used directly to dissolve the nodule (a reaction that is reported to go very quickly). In either case, the manganese is dissolved whether it is ultimately desired as a product or not. The process is particularly attractive to companies that have sulfur dioxide to dispose of (from, for example, copper smelters), but it is also regarded as a difficult process in which to control pollution.

A fourth process, also one in which essentially the entire nodule is dissolved, is that developed by Deepsea Ventures as the basis of its commercial plans. The crushed nodules are reacted with hydrogen chloride at temperatures such that most of the metals except iron are converted to soluble metal chlorides. (As a by-product, hydrogen chloride is converted into chlorine gas.) The metal chlorides are then dissolved in water and separated into aqueous solutions of nickel, cobalt, and copper salts by a liquid-ion-exchange process. From these solutions, pure metal is produced in electrolytic cells. Manganese is recovered separately. According to P. H. Cardwell of Deepsea Ventures, the advantages of the process include the high recovery rate (better than 95 percent of the metal content of the ore is recovered) and the fact that the solvents used are recycled, thus minimizing pollution.

Environmental Effects a Concern

Nodules are found in areas of the ocean that are in many respects biological deserts, but that does not mean mining will have no effect on the ocean environment. The potential problems include local disruption of the sea floor ecosystem, and distribution of sediment particles—some of which may remain suspended for a year—throughout the water column. The sediment might alter chemical balances both in the more populated surface waters and below, and as it settles out may bury organisms that live on the sea floor. Many oceanographers do not believe that mining itself will do much permanent damage to the oceans as a whole, however, because of the relatively small areas to be affected, but they point out that it may destroy sediment records of scientific interest. More serious environmental effects may come from processing the nodules, especially if, as some have suggested, second-generation plants are built to operate at sea. Even on land, operations that involve discarding all but the copper and nickel must dispose of millions of tons of residues that contain manganese and other toxic metals in oxide form.

The impact of the new source of metals on world markets is also a controversial subject. At one extreme, deep sea mining optimists like Mero forecast a drop in metal prices within 10 years after production starts and the closing of many land mines within 20. Others, such as A. J. Rothstein and Kaufman of Deepsea Ventures, maintain that copper prices will not be affected at all in the foreseeable future and that only for cobalt are the nodules likely to cut into prices or land-based production significantly. An analysis prepared for the World Bank points out that mining of enough nodules (about 6.5 million tons) to meet the world demand for cobalt in 1967 would have provided 22 percent, 0.9 percent, and 13 percent, respectively, of the world demand for manganese, copper, and nickel. The analysis also assesses the economics of deep sea mining as uncertain, largely because of the still unknown costs of the mining itself (estimates range from about \$3 to \$30 per ton of dry nodules at dockside). It concludes that exploitation of the nodules could reduce the dependence of industrialized countries on imports of metals and could seriously affect a few of the developing countries that depend on exports for revenue.

Commercial mining operations are not likely to begin before 1977 (it takes 3 years to build a processing plant and none are now under construction), if then. The prospects probably depend in large part on what happens to the international political and legal argument over the law of the sea, although several companies have hinted that they might force the issue by mining even in the absence of an international convention. At present almost all of the major companies are actively negotiating for partners to share the estimated \$250 million investment (and the risks) of a deep sea mining venture. Kennecott, along with four other companies, last week announced a 5-year, \$50-million research program to determine mining feasibility. Even Hughes, according to Reeve, is considering a joint arrangement in which Summa Corporation would mine the nodules and others would process them. In any case, there appears to be growing conviction in the industry that deep sea mining is gathering momentum, that manganese nodules are indeed on the verge of commercial exploitation.

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