Manganese Nodule Mining [and Discussion]

K. B. Smale-Adams, G. O. Jackson and B. White

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Manganese nodule mining

By K. B. Smale-Adams and G. O. Jackson
Rio Tinto Finance and Exploration Ltd, 6 St James's Square, London SW1Y 4LD, U.K.

This paper considers the mining of manganese nodules from the deep ocean at up to 5000 m, drawing attention to the essential need for a satisfactory legal régime under which mining companies can operate with security. The necessary exploration that has to be carried out before large investment can be made is indicated and the type and size of mining site required are determined.

The paper also considers the equipment required to collect, lift and transport the nodules. The most likely form of collection and lift is hydraulic but there are considered to be substantial development problems still to be solved. This indicates the need for large scale tests before the final decision on the mining system can be completed. The paper describes briefly a test collector operated in late 1974 and early 1975.

A brief description of the possible environmental problems is also included.

In considering the opportunities for commercial exploitation of manganese nodules one is indeed moving into deep water in all the senses that the phrase implies. This paper sets out to isolate and highlight those factors for consideration in planning a mining system. Most of the information is based on published information but we do in addition have the benefit of direct involvement with the Kennecott Copper Corporation. Clearly at this stage we are bound to some extent by confidentiality and commercial security and it is necessary to say that the views expressed are entirely personal and do not necessarily represent any corporate philosophy.

INTERNATIONAL RÉGIME

In speculating on the possibilities for economic exploitation one major difficulty is the lack of a legal régime. We feel it is necessary once again to repeat the urgency for some form of international legislation, or failing agreement at the current Law of the Sea Conference, national (reciprocal) legislation by those countries with the technological capability, to protect mining companies and to ensure the orderly development of this important new source of minerals for the benefit of mankind as a whole.

The régime should allow provisions for exclusivity and for security of tenure for the operator, adequate financial incentive to encourage development, bilateral or multilateral tax reciprocity, and at the same time a set of working regulations, environmental protection arrangements, and detailed financial provisions that will allow efficient utilization of the resource and a fair distribution of any rewards deriving from its exploitation.

Few operators would contemplate land-based operations without these fundamental provisions, and with the added risks to which a deep ocean operation would be exposed they are considered important and urgent. At the same time all mine operators recognize the status of the landlord or mineral rights owner – in this case 'the common heritage of mankind'.

THE RESOURCE

In order to plan any mining operation one needs first to identify the orebody. Perhaps we should begin with the consideration of the total reserves available and the means of assessing the recoverable mineral content. There is little doubt that there is a potentially very large resource on the sea bed; there is also little doubt that given the opportunity, a number of potential operations will be offered for financing in the next 10–20 years.

There are no 'mine sites' yet identified as such, simply because none have yet been explored to the degree necessary for this purpose, at least as far as published information is concerned. Deep Sea Ventures have laid claim to one area of 60000 km² between the Clarion and Clipperton Fault Zones and with three other consortia exploring in the Pacific it is likely that they too can identify 'areas of interest' leading to mine site development proposals. To put mine site identification into perspective, however, we have considered the occurrence of copper in Peru as an analogy in regard to mining development. Individual copper occurrences in that country number more than 500 and at first sight give an exaggerated idea of the potential reserves for exploitation. This, we hope, brings home the difference between an occurrence and a mine site. In a previous publication parameters necessary for a manganese nodule 'mine site' were identified as approximately an area of 30000 km² with an abundance of 10 kg (dry)/m² at a grade of 1.3–1.4 % nickel, 1.1–1.2 % copper and 0.2–0.25 % cobalt.

EXPLORATION AND SAMPLING

In order to assess the metal content of such a site with a confidence level of 90 % one requires at least 300 samples spaced on a lattice of approximately 10 km.

Samples are collected by free-fall samplers each comprising a set of clamshell type jaws mounted in a frame with concrete weights, a trigger, a float, a light and a transponder. These samplers are dropped overboard and sink to the bottom. When the trigger mechanism touches the sea bed the weights are released, the grabs close on the sample material and the float raises the sampler to the surface, where it can either be located by its light or from the transponder signal.

Additionally, box cores are used for lifting undisturbed *in situ* samples from the sea floor. It is possible to photograph the sample location on the sea floor just before the sample is collected.

Photography is used in its own right extensively for assessing nodule abundance on the sea floor, by counting individual nodules on each photograph. At least 30000 photographs are available to us for this purpose. Television cameras equipped with videotape have also been of assistance as an additional means of assessing the abundance and the general nature of the bottom.

One also requires a topographical relief map to give assurance that any equipment on the sea bottom could be capable of negotiating the area to be traversed.

Sea mounts are not unknown on the ocean bed but generally speaking the sea bottom representation of a mine site has been compared to the rolling hills of Western Kansas, with slopes in excess of 6° rare (but present) and an occasional outcrop of soft volcanic ash or basalt protruding above the soft sediment. Since the occurrence of outcrops, especially basalt, could pose a potential hazard to mining equipment, an analysis of their frequency of occurrence and a means of avoiding and/or surviving collisions needs to be carried out as part of any determination of recoverable reserves.

Analysis of one area has indicated that these outcrops can range from a few feet to more than 20 ft and occur randomly at distances from a few hundred to over 20000 feet and appear to occur in clusters. Their occurrence is more frequent in areas of extreme slopes and large-scale features but they are also found in relatively flat areas. In any mine site it has been assumed that approximately 25–30 % of the area would be inaccessible to mining. The nodules lie in a single layer on a soft mud floor requiring very low bearing pressure on the contact surfaces of any equipment designed for nodule collection.

Navigation

It has always been assumed if one is lucky enough to discover a mineral deposit in the deep ocean that one will be able to relocate it accurately and mine it in the exact configuration one wishes. Accuracy of location of samples and subsequent navigational control are therefore of paramount importance in planning the operation. On land one can be as accurate as the mining system allows, but in the deep oceans available long-range navigation systems mean that one may be up to 200 m from the point at which one aims. That point in turn can be 200 m away from where it has been plotted. This requires the establishment of a local navigational system with multi-ties for accuracy. The most accurate navigational aids are generally limited to a couple of hundred miles in range and are applicable to coastal waters. However, the longer-range low-accuracy systems, when integrated with a surface buoy system can be used in deep ocean navigation and within a given area accuracy is within 20 m. Having established a local grid the most efficient means of navigating beneath the surface is by the use of an acoustic beacon network where again accuracies of 15–20 m can be achieved.

A new development considered highly accurate is the Navstar Global Positioning System, consisting of 24 satellites in subsynchronous 12 h orbits. A minimum of four satellites will be in the range of any point on the globe at all times, allowing a three-dimensional fix worldwide. The system needs development, but it may substitute for the local system in the longer term.

Other mine site considerations

In our postulated mine site we have already assumed that 20–30 % of the area is inaccessible because of the topography. It would be reasonable to assume that parts of the area will also be of poor abundance and grade and one needs to consider for maximum recovery the need to avoid repeating traverses so that necessarily an unmined swathe is left between each run of the mining equipment. Once traversed by this equipment the surface-bearing pressure of the mud is lowered considerably. Nor is the mining equipment likely to pick up all of the nodules within the area of traverses. Combining these factors gives one a very low overall recovery efficiency within a mine site area and we have little reason to change the likely figure of 25 %. Improvement to a figure nearer 40 % can reasonably be expected in the second generation.

The theme we are trying to convey is that in spite of the 'enormous' overall reserves, the difficulties associated with its distribution, abundance, grade and value coupled with difficulty of access, extreme weather conditions and navigational surface difficulties are equally formidable. The lack of operating experience inhibits confidence but the prospect of challenge and subsequent reward are such that the four major mining consortia are interested in the possibilities for commercial exploitation.

Vast amounts of capital will be necessary and it is unlikely that mining companies will expend that capital other than with the support of their governments, their bankers and their technological advisers. It would seem a pity if the advance of science, or at least of technology, were to be inhibited by the law, or the lack of it, for peaceful purposes.

Having considered the nature of the resource, and its distribution, much ingenuity has been used to devise mining systems which will collect the nodules efficiently. The capital costs involved in mining at sea have such a high threshold value that it is imperative for economic reasons to mine on a large scale. Typically this would at 3–4 Mt/a. Allowing for down-time this is equivalent to 10–15 kt/day. The latter figure represents the expenditure of no less than 4 MW of power simply to raise the nodules against gravity from 5 km. Somewhat smaller mining systems can be considered if a market for manganese can be secured in addition to sales of nickel, copper and cobalt. A mining system for nodules is conventionally divided into four main components: (*a*) the collector, (*b*) the lift system, (*c*) the mining vessel, and (*d*) the transport vessels.

(*a*) *The collector*

Since the nodules lie in a single layer at the sea bottom, any collection device must sweep a large area per unit time to gather a larger quantity of nodules. Both mechanical (rakes, buckets, scoops, etc.) and hydraulic (suction dredge) types of collection have been considered. Because the sea bottom in prime nodule areas is composed of a soft, cohesive clay, mechanical devices, for example, are liable to fill with clay when dragged on the bottom, thus probably losing a good percentage of the nodules.

Hydraulic dredge systems work effectively in the clay bottom; however, the direct suction of the nodules results in a dilute slurry which can be expensive to lift unless means can be found to improve the slurry density during collection. Thus, slurry concentration is required on the collector prior to lift pumping.

Both self-propelled and towed collectors have been considered. The self-propelled collector has the advantage of having some directional and speed control, but has been found to present several difficult design problems:

(i) Traction on a clay bottom is difficult to achieve, particularly bearing in mind the very low bearing pressure of the mud floor.

(ii) With self-propulsion the lift pipe is nearly vertical, requiring a heavy collector and high power on the collector. Furthermore, small depth changes require substantial alteration of lift pipe scope.

In one version of a collector, the manganese nodules are collected by hydraulic suction, possibly with the aid of mechanical or hydraulic nodule-dislodging devices such as tines or water jets. The feasibility of the hydraulic suction process has been well established by sea trials and other land based tests. The quantity of nodules lifted by such a typical collector depends on the average nodule abundance, the width and forward speed of the collector, and the efficiency with which the collector works. Efficiency can be decreased not only simply because nodules fail to be raised, but because it is difficult to ensure that the whole frontal area of the collector is full utilized. With these limitations in mind a typical collector would be 10–15 m in width.

Nodules, sediment, other solids and water are sucked into a collector by the flow generated by a pump located near the collector head. It will probably be necessary to provide some means of concentrating the sediment–water mixture, perhaps by taking advantage of the significant difference in settling velocities between diluted sediment fines and the nodules. There is, however, an unavoidable loss of nodules at this point. The solid particle concentration of the slurry in the lift pipe is likely to be between 10 and 15 % by volume. It is possible that heavier solids (such as large pieces of basalt) can be removed at this stage and do not therefore pass into the feed pipe.

It is possible that some obstacle detection capability needs to be incorporated into the design of the collector and that short-term avoidance may need to be carried out in order to avoid obstacles not previously identified by either the mining vessel or the mine pre-survey. Such encounters will, however, shorten the availability of the collector for normal mining operations. The maximum height and shape of solid obstacles that can be accommodated by the collector is an important design variable of the collector and normally has repercussions both on the detail necessary on the mine survey plan and the steering control necessary on the sea bottom.

The collector needs up to several hundred kilowatts of electric power to operate the suction pumps, metering devices and instrumentation. Power and instrument cables and connections have to be designed to withstand the enormous pressure at 5 km. Submerged electric motors have also presented a challenge to technology but this problem has been overcome on a test scale.

The instruments and sensors in the collector need to carry out the following functions: obstacle detection, communications, performance evaluation, and operation monitoring.

A successful demonstration of a hydraulic suction collection device was carried out in late 1974 and early 1975 at approximately 5000 m. The scaled-down model used in this test was designed to be towed over the ocean floor at depths ranging from 4 to 6 km by a special, steel-armoured, electromechanical power cable. The vehicle tow velocity was approximately 2 knots (1 m/s) with an expected speed range of 3 m/s. The front section of the vehicle was designed to accommodate obstacles and surface irregularities and to be capable of surviving direct frontal vertical wall-type impacts without structural damage. In case the vehicle capsized, a design was developed which would permit it to roll back into the normal tow position.

The test was operated at a collection rate of 2 kt/day in a real mine situation. This success has given encouragement to proceed to the development of integrated tests of both collection and lifting nodules.

Instrumentation was fitted to detect, measure and record the following:

(*a*) nodule mass flow through the duct system;
(*b*) duct flow velocity;
(*c*) vehicle forward velocity and acceleration;
(*d*) vehicle heave displacement;
(*e*) vehicle pitch displacement;
(*f*) collector head heave displacement;
(*g*) relative position of vehicle to bottom;
(*h*) vehicle depth;
(*i*) tow force at vehicle tow point.

In addition, a forward-looking camera was built into the nose section of the vehicle.

(*b*) *The lift system*

Other than the collector, the lift represents the most critical element of the mining system. It must be designed to carry the high loads imposed by its own weight and the hydrodynamic towing forces. Various methods for lifting nodules have been considered, both mechanical and hydraulic. These have included the following:

(i) mechanical lift:
  continuous line bucket (c.l.b.);
  dragline bucket;
  batch lift.
(ii) hydraulic lift:
  airlift hydrocarbon or light solid particle lift;
  two pipe (with slurry injection at the collector);
  in-line centrifugal pumps, electrically driven;
  in-line centrifugal pumps, shaft driven;
  in-line mixed flow pumps, shaft driven;
  in-line axial flow pumps, shaft driven;
  in-line axial flow pumps, water turbine driven.

In general, mechanical lift systems depend on the strength of synthetic rope and the speed of traction equipment to achieve a high lift capacity. The drag-line bucket method is obviously limited by the round trip time and the size of a single bucket. The continuous-line bucket method has the advantage of running a continuous stream of buckets but is limited by the filling efficiency of the buckets, the rope strength and speed of operations. Studies have indicated that the limit set to the nodule recovery rate by synthetic ropes and the traction machinery is roughly 3 kt/day. The practical limit is probably less than this.

A batch lift method has already been proposed which does not have the limitations of rope strength of traction speed of the c.l.b. In this concept, a cable linking the mining ship to the collector simply acts as a guide for a large container which shuttles back and forth between the collector and the ship. This container is filled with nodules at the collector by means of a conveyor. Power to raise the shuttle container comes from buoyancy obtained by pumping ballast tanks empty after nodules are loaded. The container is hydrodynamically streamlined so that it accelerates to a high speed before finally docking with the ship where it is unloaded. This process was shown to have a theoretically unlimited capacity although it embodied numerous complex mechanical devices which could lead to unreliable operation.

All the hydraulic lift methods may be thought of as containing two sections; a pipe section and a pump section.

The lower two-thirds of the lift system in nearly all hydraulic methods consists of a single large diameter pipe. The exact diameter of the pipe is determined by optimizing such factors as head loss, nodule size and fabrication capabilities. For large production systems, the head losses in the lift pipe can be in excess of 10 MPa. Thus the first stage of the lift pump must be submerged over 1 km to generate the required suction without cavitating.

The differences between the various hydraulic lift methods arise from the ways of achieving this suction force in the upper section of the lift system.

Two methods, the airlift and the light solid particle lift, are designed to accomplish this by decreasing the average density of the fluid in the upper sections in order to generate upward flow. Using hydrocarbon for the same purpose raises objections on environmental pollution grounds. The airlift method operates by injecting compressed air at a depth of approximately 1–1.5 km. The hydrocarbon lift injects a light liquid instead. Both methods have the advantage of requiring no moving parts below the waterline. The airlift has several disadvantages, however:

(i) lift capacity is limited by the volume of the lift pipe which can be allowed to be occupied by air in the upper sections without causing solids to settle;

(ii) variations in load can cause system shutdown;

(iii) power requirements are higher than for an equivalent mechanical pump.

While the hydrocarbon and light solid particle lift does not present the problems encountered because of the compression and expansion of air, the density differences between available hydrocarbons or solid particles and water are so slight compared with air and water that capacities are severely limited.

Mechanical pumping methods appear to provide a feasible means for lifting nodules provided sufficient development work is carried out. The power required to raise the nodules using either airlift or mechanical pumps turns out to be of the same order and around 12–15 MW. The attractive simplicity of the airlift system, which avoids all undersea moving parts, does not require any sacrifice of power. However, no airlift system comparable in size to that required for nodules is operated anywhere in the world and there are fundamental design problems yet to be resolved.

The emergence in recent years of high-powered submerged electric motors has made it feasible to consider them as the power unit for nodule pumps. Nevertheless, there is much development work to be done to extend their power range before such pumps can be said to be proved. There does not appear to be unanimity among the various consortia on the type of pumping system that should be used.

(*c*) *The mining vessel*

The mining vessel is designed to operate in the equatorial Pacific and remain at sea for periods of up to 4 years without returning to shore facilities. The general operating ground rules dictate that all victuals, fuel, stores, repair parts and personnel be transported to the mine site and transferred to the mining ship. All logistics supplies and personnel will be transported by means of the ocean transport vessels. All normal maintenance on the mining ship needs to be carried out at sea except such maintenance that would require docking or extensive tear-down. Docking for this purpose is envisaged as occurring approximately every 4 years. The crew size is expected to be between 100 and 120 individuals, including mining staff, pipe handling crew and the ship's operating crews. Crew change is expected to occur every 30 days. Experience of this type of operation is available to oil companies in their offshore exploration programmes.

The gimbal for supporting the lift pipe needs to be considered in some detail. A roller-bearing gimbal of the required load-bearing capacity is understood to have been used in the *Hughes Glomar Explorer*. The heavy tow load requirements are unique, however, and this has resulted in the requirement that the roller bearings of the pitch axis be able to absorb axial thrust as well as radial loads.

The use of a flexure gimbal to support 35 MN is beyond what has been undertaken in the past by several orders of magnitude.

The determination of scantlings and the midship section by normal design rules is inadequate for a mining-ship design. A detailed structural design needs to be developed and a finite element analysis undertaken before the mining vessel arrangement is agreed upon.

Because of the large drag generated by the lift pipe the power requirement to drive the ship forward at up to 2 m/s can be as large as 22.5 MW. In addition, the pipe will shed eddies alternately on each side and cause the whole pipe to vibrate at a frequency of the order of 1 Hz. This can do considerable damage both to the pipe and to the ship. For both drag and oscillation reasons, fairings have to be introduced which need to be attached to the pipe as it is deployed. Even so, the towing forces are an order of magnitude larger than any ocean-going tug can provide. The large amounts of power (40–50 MW) required on a continuous basis are ideally suited to a nuclear power source and this may well be the choice in the long run. However, the construction time allied to the long-winded processes of licensing makes oil firing the only real choice for the early mining systems.

The manoeuvring capabilities of the mining vessel need to be integrated into a mining system study.

The pipe handling system dynamic analyses which have been performed have indicated that it is feasible to deploy and retrieve the pipe string with the collector attached in up to a sea state 4 at the maximum speed of 7 m/min and to tow the pipe string and collector at speeds between 1.5 and 2 m/s with fairings. The collector and pipe string can be deployed and recovered without heave-motion compensation on the pipe handling system. The pipe string must be isolated from angular roll-and-pitch ship motions in excess of 1° at all stages of deployment. This is in order to prevent excessive bending stresses from occurring in the pipe at the support point. The maximum pipe string drag angle occurring during mining operations is likely to be less than 25°.

(*d*) *Ocean transport*

The nodules, once delivered on to the mining vessel in a dilute slurry, need to be concentrated still further in order to reduce the transport costs. This concentration can be carried out either on the mining vessel or on the transport. If it is carried out on the mining vessel, which has the attraction that the concentrating equipment does not need to be duplicated on each transport, it becomes necessary to transfer solid or semi-solid material from the mining vessel to the transport vessel. If, on the other hand, slurry is concentrated after transfer it can be transferred as a slurry in a hose. In either case strict station-keeping requirements are imposed on both vessels and particularly so in the case of the solids transport. The problem is one of maintaining station for days while travelling at a relatively low speed of a few knots in a situation where sea states may be changing and where the mining vessel has to carry out a strictly predetermined set of manoeuvres. The vessels of course are themselves substantial; the mining vessel being perhaps 45000 tonnes displacement and the transport vessel of 65000 tonnes dead weight. Three or four transport vessels would maintain a continuous round trip from mining vessel to shore station. The mining vessel would contain a small buffer store of nodules in order to cope with the changeover from one transport vessel to another or to help in particularly awkward manoeuvring positions.

The environment

It is difficult to speculate on the effect on the environment of deep sea mining, but large-scale test units which are likely to be used in the next stage of commercial development will enable strict monitoring of the likely disturbances to organisms in the benthic zone to be carried out, and the effect of resettlement of disturbed sediments on bottom organisms to be examined. It will also be possible to assess the effect which the plume around the mining vessel has on light penetration of near-surface waters and of the increase in dissolved nutrients in the euphotic zone.

The deep ocean environmental studies, however, suggest that potential pollution will be minimal.

Discussion

B. White (*Department of Mineral Resources Engineering, Royal School of Mines, Prince Consort Road, London, S.W.* 7). I should like to ask about the methods used to evaluate the resources.

The box corer described collects samples of the nodules and can be likened to the diamond drill used to sample conventional ore-bodies which yields a core for assay. We are informed by most authors that the relative abundance and the metal content of the nodules is very variable over comparatively short distances.

If it is not possible to control the location of the sampling positions due to the effects of currents on these free-fall devices, what statistical techniques are used for the valuation of the resource?

K. B. Smale-Adams. I agree that *precise* control of the sampler is not possible; the deposits are not too variable within localized areas but in no areas have sufficient samples been collected to justify a high level of statistical confidence. Within any 'potential mine site areas' considerably more sampling would need to be undertaken to establish an acceptable confidence level.