DESIGN OF A TURNING CLB AND PLANNING FOR A SMALL SCALE MINING TEST

Yoshio Masuda
Japan Resources Association
Yokusuka, Japan

Michael J. Cruickshank
University of Hawaii
Honolulu, Hawaii, U.S.A.

James A. Abernathy
Capital Improvement Projects Administration
Majuro, Republic of the Marshall Islands

ABSTRACT

Recently the Government of the Republic of the Marshall Islands (RMI) applied to the Government of Japan for technical cooperation assistance to test the feasibility of cobalt crust mining using the Continuous Line Bucket (CLB) system. In preparation, components of the CLB system were designed and tested to scale including those for the ball roller parallel drive, bucket guidance and dumping, and controlling the bucket path during turning of the mining vessel. Using these test results a small scale CLB of 40 t/d capacity has been designed to test the feasibility of the Turning CLB system for crust mining on a commercial scale. It is suggested that if the Turning CLB system is suitable for mining deep seabed minerals such as crusts and nodules it will also be suitable for mining shallow water deposits such as placers and sands.

VARIATIONS IN MINING METHODS TESTED

The three principal methods originally proposed and tested for deep seabed mining of manganese nodules were a two or three phase hydraulic lift with a passive or active miner, an autonomous mining vehicle to shuttle between the seabed and the surface platform, and a continuous line bucket (CLB) system operating with a continuous loop of drag buckets attached to a flexible line. The hydraulic system has been most widely tested and is highly rated for production operations based on large economies of scale; the shuttle system is highly sophisticated but has not been sufficiently developed to test in an operating mode; the CLB system employs the least sophisticated technology and because of its simplicity, adaptability, and low cost has been proposed for the mining of high-cobalt crust at moderate production rates in the Republic of the Marshall Islands.

The CLB system consists essentially of a long endless rope loop suspended from a surface vessel to the seabed and to which are attached standard drag dredging buckets at regular intervals. Each bucket moves across the seabed at a rate, and for a period of time, determined by a combination of the rope speed, the rope slack on the bottom, and the speed and direction of the vessel from which the rotating loop is suspended. The buckets full of seabed material are continuously raised to the surface, emptied on board the vessel and returned to the seabed on the downward passage of the rope. Production rate is determined by the rope speed and the spacing of the buckets on the line.
This system has been successfully tested at sea in four different configurations:

Original CLB: The original system separated the upward line from the downward line by the ship's length, suspending them from the bow and stern of the vessel, which was then caused to move sideways by thrusters or by drifting broadside to the prevailing current. Tests were carried out off Tahiti in 1970 from the 2,500 ton Chiyoda-Maru No. 2, and off Hawaii in 1972 from the 16,000 ton Kyokoyou-Maru No. 2.

Two Ship CLB: In this case the separation of the ropes was adjusted by suspending the loop between two ships. Tests were carried out during the period 1974-76 by the French Center for Exploration of the Ocean (CNEXO).

Hydro-Dynamic CLB: Separator plates or specially configured buckets were used to separate the ropes using natural hydro-dynamic forces. Small scale tests were carried out in 1975 from the vessel Tokai University No. 2 in the Ogasawara area of Japan.

Turning CLB: By steering the mining vessel on a circular course, trailing the empty buckets over the stern and bringing up the loaded buckets amidships from inside the arc, good separation of the lines can be achieved. This method was tested in 1987 in model scale at a depth of 50 m (Figure 1) using a coastal fishing boat.

Of the four methods tested the Turning CLB is believed to be superior because of the simplicity of achieving a wide and safe separation of the two lines and the better control possible with the single, forward moving vessel.

The arc or the circular path taken by the vessel will be constrained by the nature of the deposit in which mining is taking place but it appears that seamount crust deposits may be well suited to the use of this approach.

**Figure 1. Principle of turning CLB**

**IMPROVEMENT OF THE CLB MINING SYSTEM**

The design of the traction mechanism for the CLB is a critical factor in the efficiency of the system and has been varied in each of the tests.

The mechanism used in the 1972 Hawaii test at 5000 m depth (Figure 2) used 13 traction wheels, an 85 mm rope and buckets suspended from two bails at the front and rear of each bucket. The buckets and their suspension bails were able to dump on the first vertical drop and pass through the traction wheels without removal and re-attachment. Unfortunately the large size of the mechanism prevented its use on a smaller vessel and a more compact design was adapted for subsequent tests using multiple parallel wheels (Figure 3). The drive was powered by a 33 kw, 3 speed motor and factory tests confirmed available traction forces of 4 tons at 0.2 m/s, and 2 tons at 0.4-0.8 m/s. There was, however, no way to pass the buckets through the mechanism and they would have to be
individually removed and re-attached to the line during the test. A "magic hand" crane was designed to remove the loaded buckets, dump them, and return them to the line beyond the traction mechanism. The awkwardness of this activity led to further improvements in design.

![Figure 2](image-url)  
**Figure 2. Front traction machine on Kyokuyou-Maru-No. 2**

![Figure 3](image-url)  
**Figure 3. Multi wheels traction machine**

**New Ball Roller Traction Machine**

Bail rollers were developed by Kouyou Co. in Japan for hauling large and bulky commercial fishing nets. They were used in the 1972 Hawaii CLB test for rope handling, and during the 1973 and 1975 tests on board the Tokai University vessel they were used to hoist the CLB rope with the buckets attached. Since the results in each case were
acceptable, plans were made to use the ball roller parallel drive system to replace the multi-wheel traction drive.

A cross section of a 5 ton, 60 cm ball roller for commercial CLB mining is shown in Figure 4. It consists of a pair of rubber balls inflated with high pressure air. The rope is passed between the balls and held in place by the air pressure which also supplies the holding force for the traction line. Operation is very smooth and the bucket suspension ropes can pass through the ball rollers easily. Figure 5 illustrates a factory test of parallel ball rollers driving a rope line with small buckets attached. In the full scale system eight ball rollers will be installed and driven by independent hydraulic motors in each parallel drive.

![Cross section of 5 ton, 60 cm ball roller](image)

**Figure 4. Cross section of 5 ton, 60 cm ball roller**

**Bucket Dumping Device**

Throughout many CLB tests several different kinds of dumping mechanisms have been tested. The best method involved the suspension of the bucket upside down, by its two bails. To do this the full bucket line is guided onto the deck by the first guide wheel which directs the rope to a horizontal position without twisting. The suspended buckets are then guided to a sharp vertical drop which dumps the load into a chute and the empty buckets continue through the traction mechanism (Figure 6).

In the stern, another ball roller traction device pulls the rope, and the buckets slide on a curved guide plate to the side of the stern guide wheel which delivers them back down into the sea.

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After dredging on the seafloor, the rope with filled buckets is pulled up again to the vessel and the first guide wheel to repeat the process. The design has been well tested and is considered to be reliable.

**BUCKET AND ROPE**

The only underwater parts of the CLB system are the buckets and rope. This is a simple, but important part of the mining system.
Bucket Test

Tokai University conducted 24 single line bucket dredging tests on Minami-Torishima using two kinds of buckets. There were no empty buckets from these tests, and an average 100 kg/bucket of crust was dredged without bucket loss. Both bucket types which dredged cobbles, nodules and pavement during the tests would be suitable for the CLB.

Line

Polypropylene braided or plaited line was used for the CLB tests because of its buoyancy in the water. It is weak in creep characteristics, however, and polyester or nylon rope may be more adaptable and last longer.

RESOURCES OF PACIFIC ISLAND SEAMOUNTS

Significant deposits of high-cobalt metalliferous oxides containing potential ore grades of cobalt, nickel, copper, manganese and platinum group minerals have been identified on seamounts between the depth of 800 and 2400 m in the Exclusive Economic Zones (EEZ) of many of the Pacific islands including the 5th Takuyou seamounts in the Japanese EEZ, Palmyra in the U.S. EEZ, and Labibjet, Sylvania, and Jebro seamounts in the Republic of the Marshall Islands (RMI). The latter deposits are reported to have the highest commercial potential for any Pacific Island nation.

The cobalt content of these deposits is generally higher in value than that reported for deep seabed manganese nodules which are of similar composition but are found at depths generally between 5000 and 6000 m. The amount of deposit characterization conducted to date by numerous countries including the United States, Japan, Germany, France, South Korea and others is sufficient to indicate that the high-cobalt encrustation presents a significant minerals potential, given an appropriate technology for recovery.

More important, however, is some new information concerning the physical nature of these deposits which affects the potential for their mining using the CLB system. A recent survey of the very large 5th Takuyou seamounts, which are for the most part flat topped, resulted in a series of dredge hauls recovering an average of 100 kg per bucket of cobbles, nodules, and broken pavement in a relatively short tow (Figure 7; author communication). This distribution of easily dredgeable oxide material mixed with nodules has been observed also in each of the flat topped seamounts referred to previously and may alter the concepts of dredgeability normally applied to the better known hard pavement type crusts most commonly described in the literature.

ECONOMIC ESTIMATES OF CRUST MINING AND PROCESSING IN RMI

Candidate seamounts with crust deposits in the EEZ of the Marshall Islands are shown in the map presented as Figure 8. Three of these, Labibjet (1), Sylvania (3), and Jebro (5), have been selected as prime candidates for economic evaluation. Labibjet Seamount is narrow but has a rich distribution of cobble type crust; Sylvania Seamount, located near Bikini atoll is very large and has an extensive distribution of 10-15 cm thick crust; and Jebro Seamount, located near to Majuro the capital of RMI, is well located for testing.
Figure 7. Gathered cobble type crust

Figure 8. Crust deposits and islands in Marshall Islands
Tentative Crust Mining Proposal

It is proposed to plan for a 400 ton/day mining operation out of Majuro in the RMI. A 15,000 ton vessel conversion will be fitted with a ball roller traction system using 3,000 m of 90 mm diameter rope with 1.5 m$^3$ buckets attached every 50 m. A traction rate of 0.8 m/s will require 400 kw and the buckets will be discharged automatically on board the vessel. A monthly production cycle of 20 days over 11 months each year will result in an annual production of around 88,000 tons.

Tentative Estimated Costs

The following numbers are based on data from a U.S. Environmental Impact Statement for cobalt crust in the EEZ of the Hawaiian and Johnston Islands (USDOI, 1990) and are scaled down, for illustration, to a 400 ton/day CLB operation. At a cost of 15,600 Yen/t ($120) the annual operating costs are estimated to be about Yen 1.4 billion ($10.8 million). Capital needs for the mining system are estimated to be in the region of Yen 1.5 billion ($11.5 million) and for the processing system Yen 8.5 billion ($65.5 million), for a grand total of Yen 10 billion ($77 million).

Income from sales, based on Table 1, are estimated to be Yen 9,540 million ($74 million).

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Production (t/y) (Recovery @ 80%)</th>
<th>Price (Yen/kg)</th>
<th>Income (Yx10^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cobalt</td>
<td>582</td>
<td>5,000 ($18/lb)</td>
<td>2,830</td>
</tr>
<tr>
<td>nickel</td>
<td>297</td>
<td>1,300 ($4.75/lb)</td>
<td>380</td>
</tr>
<tr>
<td>MnO$_2$*</td>
<td>24,800</td>
<td>250 ($0.90/lb)</td>
<td>6,320</td>
</tr>
<tr>
<td>Total</td>
<td>27,782</td>
<td></td>
<td>9,540 ($74x10^6)</td>
</tr>
</tbody>
</table>

* Use of battery grade MnO$_2$ is proposed for this fraction, based on existing, verified markets in Japan.

With mining costs of approximately Yen 1.4 billion ($10.8 million) and processing costs of approximately Yen 4.5 billion ($34.6 million), total costs would amount to Yen 5.9 billion ($45.4 million). This would give a gross annual profit before taxes of Yen 3.6 billion ($27.7 million) and, on the same basis, an annual return on investment of over 30%.

Small Scale Test of the CLB

In order to verify the feasibility of the CLB system in the mining scenario proposed it is necessary to operate the system in a scaled test on the RMI deposits. This can be done at 1/10 scale to produce 40 t/d by the simple conversion of an ocean going vessel at small cost. Sea trials for hydraulic systems under these conditions are inevitably much costlier.
due to the scaling effects. About 1000 tons of crust material dredged during the proposed tests would be used to develop an appropriate system for processing, thus reducing the investment risks for development of the full scale production system.

OTHER USES OF CLB TECHNOLOGY

The CLB system has been tested for manganese nodule and crust mining in water depths as great as 5,000 m. The adaptation of the system to mine placer deposits, or industrial materials such as phosphorites, sands, or gravels in coastal water depths of a few tens of meters should be quite straightforward. The mechanical improvement gained by use of the ball roller makes for a simple and reliable system of mechanical dredging in the oceans with few environmental effects. This system could well be applied to beach sand replenishment in Hawaii and other island communities where coastal protection and enhancement has become of significant economic importance.

REFERENCES


Tokai University. 1990. Cobalt-rich manganese crust: A pictorial publication by Tokai University, Cobalt RMC Investigation Group, Japan.

BENEFICIAL USES OF FERROMANGANESE MARINE MINERAL TAILINGS

John C. Wiltshire
University of Hawaii
Honolulu, Hawaii, U.S.A.

ABSTRACT

Both ferromanganese crusts and nodules present potential processors with enormous volumes of tailings of dubious environmental character; most processing scenarios fail to utilize the uneconomic manganese itself, leaving a total waste volume on the order of 96% of the incoming ore. We envision at least one scenario which could result in both the removal of tailings from a processing plant and an increase in the supply of useful building materials at little or no cost to either the processing or construction industries -- transforming a tenacious waste into a novel resource. Ongoing experiments have demonstrated considerable potential for turning acid leach tailings into dark composite facing stone, fancy black tile, novelty ceramics and concrete aggregate. It has been shown that concrete made with up to 25% tailings can have compressive strengths above 4,000 psi. Tailings melted with a small amount of flux can be made into very hard attractive ceramic tiles. Tailings can also be cold-cast or sprayed with a resin binder into an infinite variety of shapes and coatings.

INTRODUCTION

It is likely, given the interest of the Japanese, Korean, and Indian governments as well as private sector groups, that within the next twenty years there will be a marine mining operation for manganese nodules or crusts (Markussen, 1990). Such an industry could be a major economic boon to a developing Pacific island economy. This has been well recognized by the State of Hawaii which has strongly supported ferromanganese research through its marine mining program for many years. However, a serious environmental problem remains unsolved and largely unconsidered. Ferromanganese crust and nodule processing presents potential processors with enormous volumes of tailings of dubious environmental character (U.S. Department of the Interior, 1990). Most acid leach processing scenarios fail to utilize the uneconomic manganese itself, leaving a total waste volume on the order of 96% of the incoming ore. Each current disposal proposal seems flawed: (1) backhauling to the initial mine site is costly and might run afoul of EPA or UN marine dumping regulations (NOAA, 1981), (2) subsea disposal near a coastal processing site means almost inevitable community opposition (NOAA, 1981), (3) tailings ponds use large amounts of land and may run the risk of allowing heavy metals to leach into aquifers over time (Department of the Interior, 1990), (4) agricultural soil amendment for improving barren lava or coral rubble appears to require prohibitive amounts of supplementary phosphate (El Swaify and Chromec, 1985), and (5) the slag resulting from energy intensive pyrometallurgical processing may have potential as road ballast but would more likely be relegated unsightly tailings ponds (NOAA, 1981). In any case, few processors would opt for smelting in all but those locales where energy is very cheap (Johnson, 1990). This unfortunately rules out a smelting operation in almost any Pacific island environment.

We envision at least one other scenario which could result in both the removal of tailings from an acid leach processing plant and an increase in the supply of useful
building materials at little or no cost to either the processing or construction industries --
transforming a tenacious waste into a building product. Ongoing experiments have
demonstrated considerable potential for turning acid leach tailings into dark composite
facing stone, fancy black tile, specialty ceramics, or concrete aggregate (Wiltshire, 1991).

PROCESSING AND NATURE OF TAILINGS

The U.S. Bureau of Mines (Department of the Interior, 1990) has shown that,
while their extracted value metals vary widely, tailings from crusts and nodules are
essentially identical. Accordingly, results obtained from either product should prove
valid regardless of which industry ultimately unfolds. Unfortunately the original
industrial tailings from manganese nodule processing days are gone. Therefore in our
initial experiments we had to manufacture tailings by experimenting with various leach
processes. We discovered that by greatly increasing leach times, a low pressure sulfuric-
acid leach system can, in fact, duplicate the yields of an industrial high pressure leach
(Wiltshire, 1991). It was this three-metal sulfuric acid leach system which we used to
produce tailings on a bench scale processing operation. The leach technique is fully
described by Haynes, et al. (1985). All the products were geochemically analyzed for
comparison with the initial ore. Approximate yields of the process were 85% Cu and Ni
and 80% Co. This is a three-metal (Cu, Ni, Co) recovery scheme which does not recover
manganese. The leaching operation seeks to disrupt the manganese oxide crystal
structure, reducing \( \text{Mn}^{4+} \) to \( \text{Mn}^{2+} \) via the reaction \( \text{MnO}_2 + \text{H}_2\text{SO}_4 \rightarrow \text{MnSO}_4 + \text{H}_2\text{O} + 1/2 \text{O}_2 \). This disruption allows the lattice-bound Cu, Co, and Ni to be solubilized as their
sulfate salts. As the sulfuric acid is depleted, \( \text{Mn}^{2+} \) is reoxidized to \( \text{Mn}^{4+} \) and remains in
the tailings as \( \text{MnO}_2 \). The acid depletion also allows iron to precipitate as \( \text{Fe(OH)}_3 \).

CRITERION FOR THE ESTABLISHMENT OF USEFUL BUILDING PRODUCTS

The construction industry is very conservative in the acceptance of new products.
In order to be accepted new products must be fully tested. In addition, these products
must: 1) meet or exceed the properties of current products or 2) nearly equal the proper-
ties of current products but at a much lower cost. The key advantage to ferromanganese
tailings in this regard is cost. These tailings are a waste material that would cost a
processing operation an estimated $9 million a year to dispose using tailings ponds
(Loudat, et al., 1992). This means that tailings would be available at no cost to the
potential operation wishing to make building products out of them. Possibly, such a
secondary user of the tailings would receive a small fee for their removal. In the event
that the building products created used a high percentage of tailings with respect to other
constituents, the overall materials cost of the building products would be low compared to
the competing products.

The second important criterion is unusual properties of the tailings. We assume
that these would be largely due to the manganese content. In particular, manganese is
noted for its scavenging ability of other elements. This is what allowed the manganese
nodules to form in the first place. This ability may be expected to increase product
strength. Woolsey, et al. (1992) have proposed a very innovative scheme using this
property to supply coal burning electric power utilities with ground nodules as stack
cleaners. Manganese nodules have a very large surface area/volume ratio. Much of this
is still retained in the tailings. This may lead to an ability to act as a desiccator, perhaps
in turning a slow drying product into a rapidly drying product. This has a particular
application for quick drying concrete. Manganese and iron being relatively heavy

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elements will also likely give any product a greater density than it would have had otherwise. It is these unique properties as well as cost that make ferromanganese tailings an interesting material for the building products industry.

**AGGREGATES IN CONCRETE**

The American Concrete Institute (1990) has done a considerable amount of work on admixtures to concrete. This includes the successful incorporation of superplasticizers to increase concrete durability and blast furnace slag to increase strength and weight. Specially concretes for the marine environment have been given a lot of study. Another area of major ongoing research is the texturing of concrete pavements particularly to provide tough skid-resistant roadways. This is done both by sculpturing the concrete with grooves and also by adding gritty material to the concrete. Although mineral tailings other than blast furnace slag were not used directly in this work, the approaches and testing methods are applicable.

Our concrete work began by testing varying mixtures of Portland cement, coarse sand and tailings. Mixtures were made with 0-60% tailings in the concrete. Two sets of experiments were conducted. The first involved tailings which were not fully neutralized after processing (see Figure 1). These tailings had been washed and had a pH of approximately 4. They were made into standard eight inch long, four inch diameter, concrete testing cores and tested for compressive strength by a commercial concrete testing company after curing for 33 days. The sample containing no tailings had a strength of 3460 psi effectively the same as the standard value given for concrete of 3500 psi. The other samples decreased considerably in strength with increasing amount of tailings. To determine whether the decrease in strength was solely due to the tailings content, the experiment was repeated with tailings which had been fully neutralized. The results were very different. Compressive strengths above 4000 psi were achieved in concrete containing 20-25% tailings. The strength decreased fairly rapidly to 1000 psi for concrete containing 50% tailings. Although 1000 psi concrete could not be used in buildings, it would still be applicable for driveways and many other paving applications. Several non-standard size samples exhibited very high compressive strengths (in the range of 5000-6000 psi) although they contained over 40% tailings. These results are considered suspect and are being rerun.

In addition to increased strength the tailings appear to give the concrete several other interesting properties. The fine grained nature of the tailings appears to make the concrete more moldable and bubble-free. This was demonstrated in two ways. First, a moldability test was performed using a 12" by 4" latex rubber mold of an ornamental Japanese carp. The mold was made with considerable attention to fine detail. This fine detail was picked up in a casting by the concrete containing 30% finely ground tailings but not by the standard concrete. Further, the ferromanganese concrete gave a much smoother bubble-free surface. The surface textures were compared in a test by examining cut surfaces of the ferromanganese tailings concrete and a standard precast concrete brick. The ferromanganese surface had bubble pits over less than 2% of its surface. These pits ranged in size from pinholes to 2 mm in diameter averaging about 500 microns. By contrast, the precast brick had pits covering over 20% of its surface ranging to 8 mm in diameter and averaging about 2 mm in diameter. The difference was very marked. The precast brick had a rough surface the ferromanganese a very smooth surface. In addition, the tailings give the ferromanganese concrete a considerably greater density than regular concrete in that iron and manganese are being substituted for the less dense silica and aluminum of sand and the ferromanganese concrete has less than one-tenth the bubbles found in regular concrete.
Greater density and bubble reduction are two particularly important properties for concrete to be used in the marine environment or in freeze-thaw situations. In the marine environment wave action compresses air into the pores and pits of the concrete which over time breaks the concrete down. The same action results from water freezing and expanding in these pores. The lower number of pores subjected to this action the longer the concrete will endure. There is evidence to indicate that ferromanganese surfaces repel the growth of organisms (Department of the Interior, 1990). If this can be confirmed, it may be that ferromanganese concrete would not be covered as quickly with algae or encrusting organisms which would offer advantages for outfall pipes as well as many other marine and terrestrial structures.

Clearly there are considerable avenues for further research on the properties of ferromanganese tailings concrete. Initial indications of increased compressive strength, superior moldability, higher density and lower porosity give reason to believe that particularly for specialty concretes the addition of the ferromanganese waste is imparting very economically desirable characteristics. Further research will involve more rigorous testing of these properties by a commercial concrete testing laboratory.

**CERAMIC APPLICATIONS**

The second major direction of our research is geared toward the production of ceramics. This involved the melting of the tailings in a high temperature kiln alone and in combination with a variety of fluxes. The first step was to determine a melting temperature for the tailings. As might be expected the tailings do not melt at a unique
temperature but in fact melt over a range. The melting range is centered on 1280°C. This was determined using Orton ceramic cones, a standard practice in the ceramics industry. The accuracy of this method is ±20°C. The melting temperature was lowered slightly by the addition of fluxes. The tailings were introduced into the kiln as a powder at room temperature. In order to contain the melted tailings high temperature clay vessels were fabricated. After considerable experimentation, a rectangular design three inches by five inches with two inch high walls was decided on. It was made of thin walled, cone 10, high fire, raku clay. These clay holders were dried at 80°C for 24 hours before being fired to 1300°C. After cooling the powdered tailings were poured into the holders for a second firing. The kiln temperature was slowly ramped up at a rate of approximately 5°C/min. The melting temperature was held for at least one hour. Cooling rate was not monitored but took 6-8 hours to return to a temperature at which the clay holders could be removed.

The tailings alone melted to give a rough gray metallic surface. The material could be cut with a standard rock saw to give tiles of different sizes (the clay edges of the holders being cut off). The tiles did not have a uniform surface and the interior contained a large number of bubbles in the melt. The tiles suffered considerable brittleness and would break if dropped on a hard surface.

To alleviate the lack of uniformity of the melt, fluxing agents were added to the tailings. Experiments were performed using three fluxes: boric acid, borax, and lithium tetraborate. The resulting melt was a ferromanganese borosilicate glass containing 50-95% tailings. The glass melted to a perfectly smooth surface and vitreous lustre. The glass was extremely hard exhibiting a hardness of 7 on the Mohs scale. This extreme hardness makes the material of great value to the building industry because of resistance to wear. It can still be easily cut using a rock saw. The three different fluxes gave slightly different colorations. The best flux was the lithium tetraborate. In small amounts it gave the ferromanganese glass a pearly jet black finish and a dense bubble-free glass. Unfortunately, the lithium tetraborate was also the most expensive flux. Boric acid is a much cheaper flux. It gave a brown bubble-free glass but was required in higher quantities (20-40%) to achieve these results. Borax is the cheapest flux. It gave a patterned glass of somewhat less lustre. Experiments were also conducted using 0-40% basaltic sand to raise silica and aluminum contents. In general, the basaltic sand did help to produce a better glass in small amounts but the larger quantities gave little additional improvement. The resulting glasses are much denser than a normal silica glass. The chemical scavenging properties of manganese and the dense bubble-free glass may make an excellent material to encapsulate nuclear or toxic waste. The only negative properties of the glass which we encountered were brittleness leading to shattering along conchoidal fractures after impact.

We now need to take our ceramic research one step further. We have proven the concept that useful glasses can be made from manganese tailings. We have manufactured a hitherto unknown class of ceramic glasses - ferromanganese borosilicates. We have shown that these ceramic glasses have unusual and useful properties. Indeed, the glass chemistry may lead us to speculate that a series of useful electrical properties may exist which, as yet, we have not tested. We now need to optimize the products that can be made, specifically building tile. We are quantifying the solid solution melts to maximize useful properties and appearance. Once sufficient tiles of an optimized design are made, they will be sent to an independent ceramics lab for testing. This will allow an industrial evaluator to better categorize the market for the tailings products and estimate their value.
COLD CASTING AND COLD SPRAYING APPLICATIONS

Approximately a dozen building tile designs have been fabricated using a cold casting technique. This technique involves mixing of acid free tailings material with a binding agent (typically 70% tailings and 30% binder) and casting in a mold. Molds are either latex rubber or glass depending on the nature of the object to be cast. The use of rubber molds permits easy mold making of any available object or surface for duplication. Glass molds give a superior product in that the surfaces are extremely smooth and no final polishing is required. The glass molds are limited to presdesigned patterns. In general, the most successful glass molds have been made by cutting glass construction blocks in half and using the textured interior surfaces as the molds. Casting is done by pouring the liquid material (tailings plus binder) into the molds once the molds are precisely leveled on a flat surface. The molds are coated lightly with a commercial mold release to facilitate release. On hardening, which takes several hours at room temperature, the product undergoes 1-2% shrinkage which also facilitates an easy release from the mold.

The properties of the resulting cold cast tiles are largely dependent on the nature of the binding agent used. Typically, a standard grade casting resin was used for the binder. This is identical to that used in most fiberglass applications. For higher grade exterior tiles epoxy resin and marine grade epoxy resin were also used. Naturally, the strength of the tile significantly increased with the use of high-grade epoxy binder. The standard casting resin tiles failed an acid test involving submergence in concentrated acid. The tile broke down as the binder dissolved. The idea of this test is to simulate the long term effects of the exposure to acid rain. Another test found the tiles less porous to water than standard ceramic tile. A four month exposure test to intense sun and rain was conducted by covering a slanted roof top with various tile designs and comparing those with controls left indoors. At the end of the test period the exposed tiles showed some color fading as well as pitting in the size range of 0.5-1 mm covering 2-3% of the tile surface. The pitting is presumed to be an indication of tile breakdown under UV radiation. The controls left indoors showed no change. The results of these experiments indicate a stability problem for the cold cast tiles under external use if low grade casting resin is used. Work with higher grade epoxy resin will repeat the work to date.

The cold cast mix is very applicable to a range of decorative products. Its ease of moldability makes it extremely versatile in terms of the nature of the finished product. A range of art objects including small statues, turtle and fish castings, Hawaiian petroglyphs, name plates and letters have been cast. The tailings material casts very well and further takes on a lustrous sheen when polished. The shiny, lustrous, black finish of the products has, in fact, created a demand for the tailings in the University of Hawaii art department as a coating.

If the tailings are ground finely enough (fine silt to clay range) they can be sprayed with a resin from a commercial paint gun. This creates a rust prevention product which has a hard black surface. A number of biological studies have indicated that the manganese significantly resists the growth of organisms. This may mean that manganese spray coated products would be less likely to develop mildew or other bacteriological growth. It may also be a beneficial coating for corrosion resistance and reduction of organism encrustation in the marine environment. Tests are being designed to quantify these properties during in situ ocean tests.
CONCLUSIONS

In the Ukrainian Republic waste manganese fines from terrestrial mining operations have been so successfully utilized for building materials that a commercial manufacturing plant was dedicated in 1990 (Yuri Bruyakin, Moscow Mining Institute, personal communication). Osaki, et al. (1987) have had success producing light weight aggregates from marine ferromanganese tailings. We are excited at the prospect of transmuting an environmental burden into an economic asset, ameliorating one of the few major constraints to deep-sea marine mining. The production of marine-related sculpture from this most archetypal marine product must await the touch of the artist's hand, but preliminary results confirm the efficacy of producing high margin products such as ceramic tile and facing stone, along with more humble low margin assets such as concrete and brick. The predominantly dark color of these products is generally considered attractive, but offers a high heat absorbance that may have utility in solar heating products. In many scenarios these products could be introduced to remote communities that would have had to import them; in other scenarios they will have to compete favorably with long established materials that offer substantial resistance to market penetration. Even in the latter case, processors may have considerable success co-opting traditional markets by offering voluminous raw materials at highly competitive prices. This observation is key, because of an overriding concern here must be assurance of almost 100% utilization on a real time basis. Anything less would result in a backlog of tailings which require disposal by the less satisfactory means cited above.

Accordingly, our immediate challenge is establishing as many applications as soon as possible, well in advance of actual commercial mining. Each must be evaluated for physical strength, aesthetic appeal and commercial viability. With a diverse suite of options arrayed before him, a ferromanganese processor can proceed with some confidence in the inevitable disappearance of his primary waste. Whether this will result from utilization of the entire product suite or one single gluttonous market remains the great unknown. Major consumers may be industries with applications completely different from those examined here. Unexplored horizons include drilling mud and the possibility that the metal scavenging nature of ferromanganese metals may be ideal for fixing radioactive wastes in marine manganese ceramics. Either application could consume the entire output of tailings. The supreme irony would be a future wherein tailings are actually in demand, responsive to market forces and actually contributing to the income of the primary processor!

ACKNOWLEDGEMENTS

This research has been supported by the U.S. Department of the Interior's Mineral Institute Program administered by the Bureau of Mines through through the Generic Mineal Technology Center for Marine Minerals under grant number G1185128-1504. This work was also supported by the State of Hawaii Department of Business, Economic Development & Tourism and is contribution 103 of the Ocean Resources Branch.

REFERENCES


THE ECONOMICS OF MINING MANGANESE CRUST WITH RECOVERY OF PLATINUM AND PHOSPHORUS

Thomas A. Loudat and John C. Wiltshire
University of Hawaii
Honolulu, Hawaii, U.S.A.

INTRODUCTION

This study provides a new economic assessment of manganese crust mining wherein the full resource potential is evaluated. This means that the economic analysis is based on projected recoverable tonnages of platinum and phosphorite substrate as well as cobalt, nickel, copper, and ferromanganese. The additional costs to process Pt and phosphoritic substrate are also included. The analysis allows the determination of characteristics of a profitable mine site under specific mining, processing, and target metal price assumptions.

OBJECTIVES

The following research objectives are undertaken in this study:

1. Assess the resource potential of cobalt-rich manganese crusts occurring within the Hawaiian and Johnston Islands EEZ's.

2. Prepare a base case scenario under a well defined condition set within the U.S., defining all requisite systems for a one million dry ton crust per year first generation mining operation. The six crust products are: cobalt, nickel, copper, manganese, platinum, and phosphate rock.

3. Perform an economic analysis of the mining venture.
   a. Estimate the capital and operating costs of these systems in 1990 U.S. dollars.
   b. Estimate the dollar value per ton of crust mined.
   c. Perform a financial analysis of an ocean mining venture allowing the evaluation of alternative financial performance parameters.
   d. Estimate system sensitivities to different variable levels.

Achieving these objectives allows the determination of the factor set required for an ocean mining venture to be economically successful. This essentially implies the specification of a potential mine site. Achieving these objectives also allows the determination of the contribution of platinum and phosphorous recovery to the venture's profitability.

METHODOLOGY

The resource assessment estimates the crust potential of the Hawaiian Archipelago and Johnston Island. The descriptive statistics used for the resource assessment are from the crust data base compiled by Manheim and Lane-Bostwick.
(1989), Arvidson, et al. (1991) and Wiltshire (1990). The statistical data used for the resource assessment also provides the parameters required to delineate profitable mine sites within the resource area.

The basic methodology used to estimate costs is described in secondary sources (EIS, 1990; Magnuson, et al., 1985; Arthur D. Little, Inc., 1984; Bureau of the Mines, 1987; and Hillman, 1983). These sources also provide an initial conceptual design for an ocean mining venture. This design is appropriately altered to reflect specific characteristics of a venture designed to mine and process manganese crusts and recover Pt and P. Estimates of costs and activity timing are obtained from secondary sources (e.g., Magnuson, et al., 1985; Arthur D. Little, Inc., 1984; Bureau of the Mines, 1987; and Hillman, 1983), or estimated by analogy or extrapolation from cost estimates published in the literature. The base case cost per ton ore mined estimate will be for the mining scenario developed in the EIS (1990). Variations on this scenario for a sensitivity analysis will include changes in ore price, quality, percentage of substrate entrained with the ore, and metal recovery.

The price per ton of crust mined at point of processing can be determined as follows:

\[ V_c = \sum E_i P_i \]

where:

- \( V_c \) = the dollar value per ton of ocean crust mined
- \( E_i \) = recovery efficiency of product (i)
- \( P_i \) = the per unit price for product (i)
- i = 1.6

Price per pound for the respective minerals will equal a historical average price per unit for the base obtained from U.S. Bureau of the Mines historical price series. Statistics derived from the historical price data are used for selection of prices for sensitivity analyses.

Economic viability measures include: pay back periods, capital recovery rates, and internal rate of return of the before and after-tax profit streams from a hypothetical manganese crust mining and processing venture. A sensitivity analysis is performed by altering base case variable levels which also allows specification of a mine site.

**RESOURCE ASSESSMENT**

Table 1 summarizes study variables, their respective descriptive statistics, and sources for the resource potential estimation and recovery potential. Combining the resource area variable values of Table 1 with the estimated resource area, allows the estimation of the in-place resource potential of the mining area. Table 2 shows the estimated amount of crust and the respective estimates of total mineral potential for the mean values of all resource area values. To give the values some perspective, the 1990 U.S. consumption of these metals is also presented.

Table 2 shows that crusts have a substantial potential as a cobalt resource, as well as being a significant resource of Mn, Ni, and Pt. Phosphoritic substrates underlying crusts also have significant resource potential as a supply of phosphate rock for the fertilizer industry, if found and subsequently recovered with crusts of high enough grade to be mined. Using 1990 U.S. consumption levels and crust metal amounts shown in
Table 2, the Hawaiian and Johnston Island EEZ area crust resource contains 419, 181, 11, 48, and 95 years supply of Co, Mn, Ni, Pt, and P in the form of phosphate rock respectively. The Cu resource is insignificant.

Table 1. Resource area variables and values

<table>
<thead>
<tr>
<th>Variables</th>
<th>Sample Size</th>
<th>Variable Range</th>
<th>Std. Dev.</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Mean</td>
</tr>
<tr>
<td>Mean Crust Thickness (cm)</td>
<td>0.10</td>
<td>15.00</td>
<td>2.50</td>
<td>1.78</td>
</tr>
<tr>
<td>Crust Specific Gravity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet</td>
<td></td>
<td></td>
<td></td>
<td>1.95</td>
</tr>
<tr>
<td>Dry</td>
<td></td>
<td></td>
<td></td>
<td>1.34</td>
</tr>
<tr>
<td>Crust Grade</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>773</td>
<td>15.10%</td>
<td>38.79%</td>
<td>25.02%</td>
</tr>
<tr>
<td>Fe</td>
<td>802</td>
<td>5.98%</td>
<td>22.95%</td>
<td>16.89%</td>
</tr>
<tr>
<td>Co</td>
<td>806</td>
<td>0.29%</td>
<td>3.02%</td>
<td>0.87%</td>
</tr>
<tr>
<td>Ni</td>
<td>773</td>
<td>0.12%</td>
<td>1.54%</td>
<td>0.46%</td>
</tr>
<tr>
<td>Cu</td>
<td>603</td>
<td>0.01%</td>
<td>0.55%</td>
<td>0.08%</td>
</tr>
<tr>
<td>Pt (ppm)</td>
<td>8</td>
<td>0.1639</td>
<td>2.00</td>
<td>0.484</td>
</tr>
<tr>
<td>P (in phosphate rock)</td>
<td></td>
<td>0.03%</td>
<td>1.88%</td>
<td>0.51%</td>
</tr>
<tr>
<td>Crust Coverage</td>
<td></td>
<td>100%</td>
<td>40.00%</td>
<td>16.67%</td>
</tr>
<tr>
<td>Substrate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphorite</td>
<td></td>
<td>0.06%</td>
<td>29.61%</td>
<td>16.00%</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>819</td>
<td>598</td>
<td>6890</td>
<td>2012</td>
</tr>
</tbody>
</table>

Sources:
(1) EIS (1990)
(2) Manheim and Lane-Bostwick (1989)
(3) Derived from Manheim and Lane-Bostwick (1989) Appendix A, Area A-2
(4) Arvidson, et al. (1991)
(5) Wiltshire (1990)
(6) Ritchey (1988)

Note: Values are in percent moisture free material, except for Pt. It is reported in ppm.
Table 2. In-placing mining area resource potential

<table>
<thead>
<tr>
<th>Crust Weight per Unit Area</th>
<th>13,400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crust Weight (mt) per Unit Area (km sq)</td>
<td>40.00%</td>
</tr>
<tr>
<td>Crust Weight (kg) per Unit Area (m sq)</td>
<td>33.50</td>
</tr>
<tr>
<td>Crust Weight (g) per Unit Area (cm sq)</td>
<td>3.35</td>
</tr>
<tr>
<td>Average Crustal Thickness (cm)</td>
<td>2.50</td>
</tr>
<tr>
<td>Dry Weight Density (g/cm cubed)</td>
<td>1.34</td>
</tr>
</tbody>
</table>

In-Place Crust Resource

| Crust (mt) | 360,620,800 |
| Seabed Area (km sq) | 26,912 |
| Crust Weight (mt) per Unit Area (km sq) | 13,400 |

Resource Area Mineral Potential

<table>
<thead>
<tr>
<th>Metal</th>
<th>Concentration (%)</th>
<th>Amount (mt)</th>
<th>1990 U.S. Consump. (mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>25.02%</td>
<td>90,227,324</td>
<td>497,142</td>
</tr>
<tr>
<td>Fe</td>
<td>16.89%</td>
<td>60,908,853</td>
<td></td>
</tr>
<tr>
<td>Co</td>
<td>0.87%</td>
<td>3,137,401</td>
<td>7,472</td>
</tr>
<tr>
<td>Ni</td>
<td>0.46%</td>
<td>1,658,856</td>
<td>148,403</td>
</tr>
<tr>
<td>Cu</td>
<td>0.08%</td>
<td>288,497</td>
<td>2,150,000</td>
</tr>
<tr>
<td>Pt (ppm)</td>
<td>0.4840</td>
<td>175</td>
<td>3.61</td>
</tr>
<tr>
<td>P</td>
<td>0.51%</td>
<td>1,839,166</td>
<td>19,188</td>
</tr>
</tbody>
</table>

INTEGRATED MANGANESE CRUST MINING/PROCESSING SYSTEM

The integrated manganese crust mining/processing system is hypothetical since no commercial system exists. It is presumed for this study that technical investigations lead to the conclusion that profitable mine sites do exist and that a decision is made to recover and process the crusts by a corporate rather than government entity. The assumed annual system throughput is approximately 1.4 million dry tons of manganese crust and substrate delivered to shore.

The crust mining/processing venture developed for the base case scenario allows the recovery of Pt as the metal and P in the form of high concentrate phosphate rock. The respective systems required to recover and ultimately sell all recovered metals parallel others described in the literature, with appropriate changes to allow recovery of Pt and P. A brief process system description follows.
The beneficiation method is wet high intensity magnetic separation (WHIMS) which allows the recovery of high concentrate phosphate. WHIMS concentrates the phosphate rock portion of the crust/substrate complex in the non-magnetic fraction. The target metals concentrate in the magnetic fraction. Beneficiation of the non-magnetic WHIMS fraction to concentrate the phosphate rock follows standard methods and practices of the U.S. phosphate industry.

The Pt is recovered during hydrometallurgical processing of Co, Ni, and Cu. Since the Pt occurs in two distinct forms, a hydrogenetic Pt chloride complex (up to 0.5 ppm) and as elemental Pt in a Ni/Fe alloy in cosmogenic spherules (more than 0.5 ppm), two recovery pathways are required. The hydrogenetic Pt chloride dissolves in the target metal solution and is recovered as sponge Pt. The Pt in the Ni/Fe alloy remains in the target metal solution sludge. It is beneficiated using Pt beneficiation methods described in the literature to concentrate the Pt (see Bennets, et al., 1987; and Gomes, et al., 1979 and 1980). This latter pathway is only relevant if the Pt concentration exceeds 0.5 ppm. Metal recoveries from the processing system are 87.50%, 86.40%, 77.30%, 87.90%, 52.89%, 90.00% for Co, Ni, Cu, Mn, P (as P₂O₅) and Pt, respectively.

Capital and operating cost summaries are presented in Table 3. A detailed discussion of the system and respective sector cost estimates can be found in Loudat, et al. (1993).

Table 3. Cost summary (millions of 1990 dollars)

<table>
<thead>
<tr>
<th>Sector</th>
<th>Capital Costs</th>
<th>Operating Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amount</td>
<td>% Distrib.</td>
</tr>
<tr>
<td>Prospecting &amp; Exploration</td>
<td>$7.2</td>
<td>3.30%</td>
</tr>
<tr>
<td>Mining</td>
<td>$259.7</td>
<td>28.21%</td>
</tr>
<tr>
<td>Ore Marine Transport</td>
<td>$131.8</td>
<td>14.32%</td>
</tr>
<tr>
<td>Ore Marine Terminal</td>
<td>$41.8</td>
<td>4.54%</td>
</tr>
<tr>
<td>Onshore Transport</td>
<td>$17.4</td>
<td>1.89%</td>
</tr>
<tr>
<td>Processing</td>
<td>$458.7</td>
<td>49.83%</td>
</tr>
<tr>
<td>Waste Disposal</td>
<td>$9.4</td>
<td>1.02%</td>
</tr>
<tr>
<td>Mining Support</td>
<td>$1.8</td>
<td>0.20%</td>
</tr>
<tr>
<td>Research &amp; Development</td>
<td>$1.3</td>
<td>0.58%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$920.6</strong></td>
<td><strong>100.00%</strong></td>
</tr>
<tr>
<td>Estimated Annual Dry Tons Crust/Substrate Processed</td>
<td>1.33</td>
<td></td>
</tr>
<tr>
<td><strong>Cost per Ton</strong></td>
<td><strong>$164.0</strong></td>
<td></td>
</tr>
</tbody>
</table>

Integrated crust mining system capital costs would be 920.6 million 1990 dollars with a $164 dollar per ton operating cost. The processing and mining sectors account for the majority of both capital and operating costs, compromising approximately 50% and 25% respectively of each of these costs. Various possible means exist to reduce costs. These include: in situ beneficiation, in situ beneficiation and processing, and on site
sulfuric acid production. New alternative processing methods also have the potential to significantly reduce both capital and operating costs. Operating cost reductions have the greatest potential to increase the venture IRR versus capital and pre-production cost reductions.

FINANCIAL ANALYSIS

The financial analysis was conducted using a spreadsheet model similar to that presented in Magnuson, et al. (1985). The model allows the calculation of the pay-back period (in years), capital recovery factors, and internal rate of return on investment.

The per ton crust/substrate values are derived from the metal recoveries per ton ore/substrate and the metal prices. Table 4 below shows the relevant data and the value per ton of the ore/substrate for the base case scenario.

Table 4. Ore value per ton

<table>
<thead>
<tr>
<th>Metal Product</th>
<th>Metal Recoveries</th>
<th>Recovery per Ton Ore Processed</th>
<th>Annual Metal Weight Recovered</th>
<th>Base Case Metal Price (mil.$)</th>
<th>Annual Metal Revenue (mil.$)</th>
<th>% of Total Revenues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode Co (lbs)</td>
<td>87.50%</td>
<td>0.61%</td>
<td>17,904,031</td>
<td>$14.93</td>
<td>$267.33</td>
<td>86.14%</td>
</tr>
<tr>
<td>Cathode Ni (lbs)</td>
<td>86.40%</td>
<td>0.32%</td>
<td>9,347,492</td>
<td>$3.68</td>
<td>$34.43</td>
<td>11.09%</td>
</tr>
<tr>
<td>Cathode Cu (lbs)</td>
<td>77.30%</td>
<td>0.05%</td>
<td>1,454,431</td>
<td>$1.30</td>
<td>$1.90</td>
<td>0.61%</td>
</tr>
<tr>
<td>Mn (metric ton)</td>
<td>90.00%</td>
<td>18.09%</td>
<td>240,225</td>
<td>$2.20</td>
<td>$0.53</td>
<td>0.17%</td>
</tr>
<tr>
<td>P (30% P2O5 material) (mt)</td>
<td>52.89%</td>
<td>2.87%</td>
<td>38,123</td>
<td>$28.23</td>
<td>$1.08</td>
<td>0.35%</td>
</tr>
<tr>
<td>Sponge Pt (troy oz)</td>
<td>90.00%</td>
<td>0.000035%</td>
<td>14,941</td>
<td>$339.38</td>
<td>$5.07</td>
<td>1.63%</td>
</tr>
<tr>
<td>Sludge Pt (150ppm) (troy oz)</td>
<td>0.00%</td>
<td>0.000000%</td>
<td>0</td>
<td>$321.88</td>
<td>$0.00</td>
<td>0.00%</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>$310.33</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dry Tons of Crust/Substrate Processed per Year</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>1,327,923</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ore Value per Ton Crust/Substrate Processed</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>$233.69</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE: Sponge and sludge Pt are approximately 75% of quoted Pt prices. Sludge Pt prices are further reduced by $17.50 per ounce for the cost of its treatment to recover Pt values. (Personal Communications with Allen Reikin of Constrade Mineral & Metals, Inc.)

Clearly, the largest revenue producer is cobalt comprising almost 90% of total annual revenues under the base case scenario. Pt is the third largest revenue producer exceeding Cu, Mn, and phosphate rock. The Pt percentage of ore value per ton increases to over 6% for 2 ppm crust Pt. When a phosphoritic substrate is encountered, its percentage of ore value per ton increase 2.5 time relative to the base case. If the phosphorite occurs as the major mineralogical phase in the substrate, the phosphates percentage of total ore value increases 6 times relative to the base case.
FINANCIAL ANALYSIS BASIC ASSUMPTION SET

To obtain a meaningful financial analysis, a number of conservative assumptions have been made. These are as follows:

1. The crust mining venture is a corporate subsidiary of a parent mining company organized specifically for undertaking the proposed mining venture. The parent company can shield other net income from taxes using pre-production losses from the ocean mining venture. The venture is a technical and management success.

2. Capital and operating costs of any non-standard regulatory regime, if incurred, do not significantly alter estimated returns.

3. Because of the high degree of uncertainty predicting inflation over a 20 year horizon, average annual cost and price inflation over the 20 year life of the venture are assumed to be equal. Thus, no inflationary adjustments are made and all analysis financial variables (e.g., IRR) are expressed in real terms.

4. The pre-production tax rate is 40.8%, the maximum federal plus state corporate income tax rate. The tax rate incurred (post-tax credits) on the venture once production commences equals the average for U.S. mining sector companies with assets greater than $250,000,000 in 1988 increased by 20% to account for State corporate income taxes. The tax rate on net income equals 22.77% (see IRS, 1991). This rate implicitly incorporates (average) depletion allowances such a venture would obtain.

5. The parent company successfully obtains financing. Financing is 25% from parent equity capital and 75% debt financed. The annual real (i.e., reduced by inflation) interest expense is 5%. The debt is amortized over the 20 year life of the operation.

6. Cost of sales equals 2.5% of gross revenues. This includes tolling charges, commissions, and discounts.

7. Pre-production capital costs and equity contributed by the parent company are expensed the year they occur.

8. All equipment functions for the expected 20-year life of the project. Maintenance and repair annual operating costs provide for any necessary replacements.

9. Straight-line depreciation is used to depreciate all fixed plant and equipment capital. This does not include pre-production capital expenditures or capital expenditures expensed.

10. Working capital is contributed by the parent company the year production commences. Average working capital balances remain constant over the life of the venture and earn an average annual 3% real rate of return.

11. Working capital and land costs are recaptured the last year of the operation.

12. Plant and equipment salvage value equals cleanup costs. Thus, there is a $0 net plant and equipment salvage value.
ANALYSIS RESULTS

The economic analysis performed indicates that the assumed venture leads to significant savings to the mining venture parent company. This results from tax structure and expensing assumptions made. The tax savings significantly improve the economic performance of the venture such that post-tax internal rates of return (IRR) exceed pre-tax IRR’s. Platinum and phosphorus both contribute to venture profitability. Pt increases the venture IRR when its crust concentration is in the 1.5 ppm range. This means that a cosmogenic fraction must be present for Pt to make positive contributions to venture profitability. Phosphorous recovery increases venture profitability at assumed base case grades, recoveries, and prices. Assuming a phosphoritic substrate occurs as the major mineralogical phase in the substrate, its recovery increases the venture IRR by almost 10%. Phosphorous recovery also dampens the negative impact on venture profitability if the base case substrate dilution rate (i.e., 25%) is not achieved. Pt and P price changes do not have significant impacts on venture profitability given their relatively small proportions of venture gross revenues.

The most important factor contributing to the success (i.e., increasing the IRR) of the manganese crust mining venture is cobalt price. Cobalt prices in the $20 per pound range, all else constant, provide a venture internal rate of return (i.e., IRR) of approximately 25%. Given their volatility however, such a Co price regime should not be relied upon for the success of the venture, in spite of current Co prices considerably above $20 per pound. Changes in Co grade also have a significant impact on the venture IRR and consequently its success. A cobalt crust grade of 1.25%, all else constant, leads to an IRR in excess of 25%.

Increasing Co recovery by 1% leads to an almost 3% increase in venture IRR. Preliminary investigations suggest that froth flotation may prove a more profitable beneficiation method than wet high intensity magnetic separation (WHIMS) assumed for this study, even though this means no P recovery. That is, the positive marginal contribution to venture profitability from recovering P, may be less than the cost of lower Co recoveries using WHIMS.

The most significant downside risks to the success of an ocean mining venture from this analysis are low cobalt prices and high substrate dilution rates. At slightly less than $13 per pound Co, the venture IRR equals 0. Cobalt prices represent the economic variable least controllable by the mining venture. The substrate dilution rate represents the major technical uncertainty in mining manganese crusts. A substrate dilution rate of only 5% above the base case value of 25%, reduces venture profitability by almost 50%. This suggests that if technical aspects of actual crust mining experience are significantly outside of ranges indicated in the EIS (1990), the venture would not likely be profitable.

CONCLUSION

A 1.25% crust grade of cobalt can serve as a minimum grade necessary for identifying crust mine sites and thus adding to U.S. cobalt reserves. Assuming Co grade is normally distributed, such a grade should occur approximately 15% of the time in the resource area. If this is the case, potential mine site(s) could support approximately 27 years of profitable crust mining at this grade cobalt, all else constant.

Table 5 presents the financial results of mining a crust cobalt grade of 1.25%. Since Mn and Ni grades are highly correlated with Co grade, their grades are
correspondingly increased as well (Mn = 30.19%, Ni = 0.866%). The post-tax internal rate of return is 30.59%, a noteworthy return even with the inherent risks of mining manganese crusts. Assuming a 1.75 Pt crust grade, the Table 6 IRR increases to 32.02%. Further assuming a major phase phosphoritic substrate this IRR increases to 32.37%.

Table 5. Mine site assumption set results

<table>
<thead>
<tr>
<th>ASSESSMENT VARIABLES</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capital Expenditures</strong></td>
<td></td>
</tr>
<tr>
<td>Fixed Capital Investment</td>
<td>$819.2</td>
</tr>
<tr>
<td>Pre-Production + Parent Fixed Capital</td>
<td>$600.5</td>
</tr>
<tr>
<td><strong>Tax Savings</strong></td>
<td>$(262.8)</td>
</tr>
<tr>
<td>Net Parent Capital Funding</td>
<td>$337.7</td>
</tr>
<tr>
<td><strong>Pay Back Periods (in years)</strong></td>
<td></td>
</tr>
<tr>
<td>On Fixed Capital</td>
<td>4.45</td>
</tr>
<tr>
<td>On Net Parent Capital Funding</td>
<td>1.83</td>
</tr>
<tr>
<td><strong>Real Rates of Return</strong></td>
<td></td>
</tr>
<tr>
<td>Return on Fixed Capital</td>
<td>22.50%</td>
</tr>
<tr>
<td>Return on Net Parent Capital Funding</td>
<td>54.57%</td>
</tr>
<tr>
<td>Internal Rate of Return</td>
<td>21.43%</td>
</tr>
</tbody>
</table>

PRE-TAX     | POST-TAX

This assessment begs issues of crust thickness, contiguity, and microtopography which could impact the feasibility of mining a mine site as defined herein. Nonetheless, these issues do not diminish the conclusion of this paper that under a reasonable crust mining/processing scenario, cost and price structure, and well within observed crust grades, a crust mining venture has the potential to be successful.

ACKNOWLEDGEMENTS

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THE POTENTIAL ROLE OF PASSIVE SONAR IN FISHERIES RESOURCE EVALUATION

William E. Evans and Jeffrey C. Norris
Texas A&M University
Galveston, Texas, U.S.A.

ABSTRACT

When sonar detection of marine organisms is mentioned most every one visualizes one of a vast array of fish finding active sonars. This is because passive systems have been essentially limited to military use. Submarines like to run deep and silent; therefore, sensitive listening systems are essential. In the process of developing and improving passive sonars, i.e. listening sonars rather than pinging, for the Navy's surface and sub-surface fleet, a vast variety of biological noise generators have been documented. Many fishes and most crustaceans are either direct or incidental noise makers. Many fishes actively produce sounds which are associated with courtship and territoriality. Some fishes and most crustaceans generate mechanical sound by movement, feeding and other activities. In many cases, sound generating fishes (e.g. croakers, drums, sea robins) can be identified to genus and in some cases species. Large schools of pelagic fishes, especially the tunas, make mechanical noise associated with swimming and feeding.

Over the past two decades passive sonar instrumentation and analytical techniques have become very sophisticated. In 1980, a special towed linear array passive sonar system was developed. A modified version of this array is being evaluated in the North Western Gulf of Mexico to survey demersal fishes and penaeid shrimp. Distribution as determined by acoustic contacts will be compared with the distribution and density of several target species determined using conventional bottom trawling.

INTRODUCTION

Assessing the abundance and distribution of marine animals populations, e.g. mammals, fish, and crustaceans, is fundamental to responsible management of ocean resources. Existing assessment techniques use a combination of fishery catch records, visual censuses, experimental net hauls, and active acoustics surveys (SONAR) (Johannesson and Mitson, 1983). Investigations in fisheries biology and the fishing industry encourage research and development of new assessment techniques that can detect, locate, and estimate the abundance of commercially valuable marine organisms.

Many marine animals produce sounds, either by active vocalizations or incidentally while swimming or feeding, e.g. scombrids, scænids, scorpænids, most penæid and sergestid shrimps, and marine mammals. As many as sixteen species of fish and marine invertebrates found in the Gulf of Mexico are known sound makers (Fish and Mowbray, 1970). Examples of biological sources of sustained ambient noise as discussed by Myrberg 1978 are presented in Figure 1. Using acoustic monitoring to detect and locate sound-producing organisms has been suggested, but problems associated with monitoring mobile species has limited studies to evaluating stationary resources. Takemura (1972), in a paper describing the distribution of biological underwater noise in the coastal waters of Japan, demonstrates an excellent relationship between the
distribution of "frying noise" usually associated with snapping shrimp and valuable fisheries resources.

EXAMPLES OF BIOLOGICAL SOURCES OF SUSTAINED AMBIENT NOISE

A. CROAKER CHORUS (FISH, 1953)
B. CROAKER CHORUS (FISH, 1953)
C. SEA TROUT CHORUS (FISH & CUMMINGS, 1972)
D. EVENING CHORUS: ATTRIBUTED TO SEA URCHINS (TAIT & MCADAM IN FISH, 1964)
E. SNAPPING SHRIMP ON SPONGE BED (TAVOLGA, 1974)
F. " (KNUDSON ET AL., 1948)
G. " (AUB et al., 1973)

Figure 1. Acoustic spectra of several examples of biological sources of sustained ambient noise

In the late 1960's and early 1970's, the U.S. Navy started to address a similar problem in anti-submarine warfare: acoustically tracking mobile underwater targets (submarines) to determine their abundance and distribution as a function of time. The Navy benefitted from technological transfer by testing the effectiveness of hydroacoustic streamers (towed linear arrays of hydrophones) that had been first used for seismic exploration by the oil and gas industry as the receiving system of a new passive sonar system. The transfer worked. Towed acoustic array technology, coupled with the rapidly improving computer data analysis capability produced a sensitive, mobile, range detecting and tracking passive sonar. Now, after a decade and a half of Navy experience, the stage was set to transfer this capability to the detecting, locating, and assessing of biological targets, many of which constitute a major source of noise for the Naval anti-submarine warfare applications.

In 1980, a towed linear acoustic array, specially tuned to optimize the reception of biological signals, was designed for Sea World Incorporated by George Anderson with the assistance of the authors. With the support of Sea World Inc., U.S. Tuna Research Foundation, National Marine Fisheries Service, and the Office of Naval Research this
new array was initially tested at sea by scientists from the Hubbs Sea World Research Institute in San Diego, California. The initial tests were more successful than anticipated and demonstrated that a properly designed system:

- can detect and classify various species of marine mammals, in many cases well beyond visual detection range
- had the potential for detecting various species of commercial fish stocks, such as drum, croakers, and other phonating species
- demonstrated that non-vocalizing species, such as large schooling fishes such as tunas produce sounds associated with swimming, feeding, and other activities which involve opening and closing the mouth.

The linear acoustic array used in the initial tests had several distinct advantages over other systems we had used in the past. Hydrophone groups could be spatially arranged for optimal reception of specific frequency bands to optimize detection of certain species. Array depth could also be adjusted for optimum sound reception as a function of target depth and prevalent oceanographic conditions. The directional sensitivity of the array could be used to minimize ship self-noise. The array could be modified electronically to form narrow reception beams which facilitate the tracking of specific targets. In addition, the array proved to be easily transported and adaptable for use on a variety of boats and ships and easy to repair at sea.

These initial trials demonstrated that passive-acoustic analysis techniques coupled with acoustic array technology had significant potential for advances in bio-acoustic research and, possibly, in the future as a tool to improve the evaluation of fisheries resources. The refinement of these techniques is the direction for our future research.

**OBJECTIVES**

The goal of our continued research is to evaluate the effectiveness of various array configurations as non-disruptive methods of detecting, locating, and estimating the abundance and distribution of marine animals. The distance and direction to the animals relative to the ship could be determined by 1) knowing the directional characteristics of the array, 2) the acoustic source level of the various biological targets and 3) then, developing a computer program which then estimates the distance to these targets. Identity of the marine animals can be determined using a statistical program for isolating components of the acoustic signature similar to the techniques suggested by Fristrup and Watkins (1992).

At the present there are no clear methods for determining abundance on any more than a qualitative basis. Rate of calling and call density can provide some estimate of abundance. In the cases where individuals, groups, or stocks can be identified by the nature of their calls, e.g. sperm whales (Watkins, 1977), humpback whales (Payne and Grunee, 1983), killer whales (Ford and Fisher, 1982), and bottenose dolphins (Caldwell, et al, 1990) numbers can be determined with greater accuracy. Data on individual identification of fishes are generally not available. In the case where certain species call individually during certain seasons of the year (croakers, toad fish), individual differences in call structure may exist and would allow for more precision in estimating abundance.
Our current research using passive sonar technology, focused on the Gulf of Mexico, includes a visual and acoustic survey of cetaceans from the Texas-Mexico border eastward to the Alabama-Florida border off shore from the 100 meter isobath to the 2000 meter isobath (Figure 2). This program (GulfCet) is sponsored by Minerals Management Service. A companion program (LATEX) which is a comprehensive oceanographic/hydrographic study of the Louisiana-Texas continental shelf is also funded by Minerals Management Service.

Figure 2. Map of the census area, from the Texas-Mexico border eastward to the Alabama-Florida border, off shore from the 100 meter isobath to the 2000-meter isobath.

Although the main emphasis of the GulfCet program is endangered marine mammals, we are also pulling the array through areas of high densities of several species of demersal fishes and penaeid shrimp. In 1983 the Minerals Management Service published an atlas of the demersal fishes and shrimp of the soft bottoms of the continental shelf from the Rio Grande River to the Mississippi Delta. Excerpts of species lists and maps of the study area are presented in the Northwestern Gulf Shelf Bio-Atlas, Open File Report 82-04, U.S. Department of the Interior/Minerals Management Service 1983.

The towed acoustic array we are using is a modification of the original array constructed for and tested by the Hubbs Sea World Research Institute, San Diego, California. Most of the high frequency hydrophones have been replaced, and both temperature and depth modules have been installed at both the head and tail ends of the array. The array covers a frequency band from 5 Hz to 25 kHz. In order to target a broad range of species, there are three "tuned" sections or modules: a low frequency module containing eight groups of hydrophones centered at 30 Hz; single groups centered at 480 Hz, and 3.5 kHz; and two modules (front and aft) with hydrophones groups centered at 5, 10, and 15 kHz (Figure 3). The sound reception field of the array is perpendicular to the
Figure 3. Diagram of the linear acoustic array, illustrating its various components including the placement of depth and temperature sensors, and the various hydrophone groups and their respective frequency ranges.
Figure 4. A sound reception field of array
direction of the tow, thus reducing self-noise from the towing vessel (Figure 4). Incoming signals are processed in real time using an on board acoustic/signal processing system. A real time frequency vs time display is monitored all the time the array is in the water. All incoming signals are recorded on an eight channel Racal Store V FM tape recorder. The frequency response of the system is limited by the hydrophones and our choice of tape speed. The analysis system and the recorder are effective from 0-100 kHz. The signal processing system currently in use utilizes a 386 CPU and the SIGNAL System Software which provides for the real time sonagraph, FFT analyses, cross correlation, signal filtering, and weighting. An illustration of the system as installed on the R/V LONG HORN is presented in Figure 5.

Figure 5. A diagram of the system as installed on the R/V LONG HORN
We started the first GulfCet cruise on April 15, 1992. Fourteen north-south transects starting at the Mexican-Texas border were completed between April 15 and May 1, 1992. The University of Texas Oceanographic Research Vessel LONG HORN was used for the survey. In addition to the around the clock acoustic survey, a visual survey using two 26 X 150 binoculars was conducted from dawn to dusk. Two observers and a data recorder using 10X binoculars reported sightings of marine mammals, birds, sea birds, marine turtles, fish schools, ships, boats, and unusual ocean conditions. A complete suite of oceanographic samples, including XBT stations and CTD down to 1000 meters were systematically collected along the 14 north-south transects (Figure 6).

During the cruise there were 16 sightings of seven cetacean species. There were a total of 47 acoustic contacts with marine mammals, nine of these were in association with the visual contacts. The additional acoustic contacts were at night and during sea states or weather conditions when visual observations were not possible. For example, sperm whale (*Physeter macrocephalus*) were heard on five different occasions, though seen only once. There were also several suspected fish contacts, and two recordings of shrimp. Several observers have suspected that there was noise associated with the daily migration of the deep scattering layer. Results from this initial cruise have verified this suspicion.

Passive sonar technology, such as the towed array being used in the GulfCet program, has the potential of being a useful supplement to other techniques being used to evaluate fisheries resources. Large areas can be mapped rapidly since the survey technique is continuous and not limited by the availability of light or fair weather. Temperature, depth, light transmission, and salinity sensors can be installed to provide continuous corollary environmental data.

The successful development of a passive acoustic detection technology will benefit commercial, environmental, and scientific interests and, hopefully, will help in the development of effective management programs and policies by improving the accuracy of our resource population estimates.
Figure 6. Map of the locations of oceanographic samples, including XBT and CTD stations.
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