DEVELOPING A SAMPLING SYSTEM FOR SEABED CRUST DEPOSITS

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The future exploitation of cobalt-rich manganese crust deposits will require a dependable system to characterize these deposits at potential seabed mining sites. The Bureau of Mines initiated research to develop a new sampling dredge by conducting a series of laboratory physical property and cutting tests on previously collected crust and substrate samples. Using the engineering parameters derived from these data, the Bureau, with the cooperation of the Minerals Management Service and U.S. Geological Survey, designed and constructed a new sample dredge system. This system was tested during a sampling cruise aboard the RV Farnella near Johnston Island in December 1986.

The new system is capable of fragmenting and collecting in situ crust and substrate where the seabed is relatively flat. Where the seabed is rugged, the system is less effective. The research effort provided valuable input to future designs.

INTRODUCTION

Successful commercial extraction of cobalt-rich manganese crust deposits will require a dependable system that can retrieve representative samples, so the deposits can be characterized and credible estimates made of return on investment. Without such capability, the mining industry will not venture the capital necessary to exploit these potentially valuable deposits.

Many dredge designs have evolved over the past 30 years [1] for sampling seabed deposits. Among the most popular is the chain-bag dredge, primarily because of its simplicity. The chain-bag dredge (fig. 1) consists of a rectangular or circular steel frame to which lengths of chain are attached by shackles. The lengths of chain are interconnected to form a chain sleeve, and the lower end of the chain sleeve is purged together for closure. The chain-bag usually has a removable inner liner of nylon fabric.

This dredge, with its "open mouth" design, is suitable for collecting loose "talus" samples and can also break off and collect in situ material if it occurs as weak projections. It is, however, less effective on smooth ocean floor, because it lacks the ability to bite into the surface. Consequently, it cannot consistently fragment and collect competent seabed crust such as the cobalt-rich, manganese crust deposits that are of current interest. It tends to bounce and skip, resulting in sample collection over a considerable distance and depth, and because crusts are often firmly attached to hard substrate, the dredged sample may not be representative of the area of interest [2]. For mine planning, a continuous sampling system that collects in a manner similar to the probable mining system is desirable. This is based on the supposition that if a mining system includes design principles from a successfully operated sampling device, then the system ought to have a reasonably good expectation for success.

The crust deposits of interest were in the vicinity of Johnston Island at a depth of 2,000 to 3,000 m (6,500 to 9,800 ft). The primary objective of the RV Farnella sampling cruise was to obtain a bulk sample of 4,500 to 5,500 kg (10,000 to 12,000 lb) of crust and substrate material. The major portion of the sample was destined for the Bureau of Mines' Salt Lake City Research Center for extractive metallurgy research, and a smaller amount was intended for the Bureau's Twin Cities Research Center for physical property and cutting tests. Other participants were the Geological Survey of Japan and the Japan Resources Association, which were to share in the distribution of sample material.

Recognizing the limitations of existing chain-bag dredges, the U.S. Geological Survey, which had overall responsibility for the cruise, suggested that the Bureau of Mines study possible improvements in the dredge sampling system. Of particular interest was the development of a system that could fragment and collect competent in situ crust material with minimum dilution by the barren substrate. In this respect, the success of any future seabed crust mining system would depend on the extraction of this in situ material, rather than on the collection of only loose talus. The Farnella cruise presented the opportunity to test a new dredge system.

with financial support from the U.S. Minerals Management Service, the Bureau proceeded with the development of a new system. However, the
timeframe proved to be a major obstacle. The Farnella sampling cruise was originally scheduled for January 1987, but vessel scheduling problems forced the movement of the departure date to late November 1986. This unanticipated change shortened the already limited time available for design, construction, and transportation of the dredges (the primary unit plus a backup) to 6 weeks. By adhering to a rigorous schedule and proceeding with a conceptual design with a bare minimum of testing, the dredges were on board when the Farnella departed Honolulu on November 28. The accelerated schedule increased the risk of the venture, because it did not allow for full-scale on-land testing.

Using standard chain-bag dredges, the Farnella collected more than the required quantity of bulk sample at an on-bottom sampling rate of approximately 175 kg/km (700 lb/mi). The portion of the collected sample broken from in situ crust was estimated at 83 pct over 25 dredge hauls. The average dilution by the barren substrate was 80 pct. This sample material was satisfactory for its intended use.

During this sampling, one of the Bureau dredges was deployed. Because of logistics problems with the heavy Bureau dredge, which were compounded by adverse weather conditions, the test of the Bureau system was limited to one run. The dredge fragmented and collected about 30 kg (65 lb) of crust and substrate material, in spite of the fact that the seabed topography was extremely rugged - a condition not foreseen in the design. The Bureau sample contained no visible talus, and dilution by barren substrate was approximately 50 pct. This test confirmed the ability of the Bureau's cutting system to shear off competent crust and substrate.

The primary value of this exercise was the knowledge gained. Effective sampling dredges for mineral exploration and tonnage and grade estimates should incorporate a cutting system principle similar to the Bureau design in order to fragment and collect competent in situ material. This is necessary because sampling requirements for mining purposes are different than those for geologic purposes, which are concerned with such things as composition, structure, and genesis.

In addition, the dredge design cannot limit its operation to a specific seabed topography. The unpredictable ocean floor demands a system applicable to a variety of topographies, both rough and smooth. The insight gained through the design, construction, and testing of the Bureau dredge system will lead to more universally applicable dredges in the future.

**DESIGN OF BUREAU SAMPLING DREDGE**

**Design Criteria**

The Bureau dredge was designed to meet the following criteria:

1. **Ability to cut an in situ sample**

   The primary goal of the Bureau dredge was to continuously cut and collect manganese crust to a preset depth.

2. **Minimize hangup potential**

   The loss of dredges on the seafloor is a common occurrence, and one that is anticipated on any sampling cruise. The equipment may hang up behind or between projections, and with pulling capability limited to that provided by a single wire rope, such losses are inevitable with even the most careful procedures. This is one of the reasons favoring the relatively inexpensive chain-bag dredge, since they are considered "throwaways" that are easily replaceable. The more complex, and therefore more expensive, Bureau dredges did not fall into this category, so much consideration was given to minimizing the danger of hangups.

3. **Limit dredge pulling force**

   The single half-inch tow cable had a design yield strength of 133,000 N (30,000 lb), but it was necessary to limit tension to about 90,000 N (20,000 lb), as irreversible cable stretch can occur above this load.

4. **Ability to reject loose talus**

   As the primary duties of the Bureau sampling dredges were to fragment and collect competent in situ crust material, it was necessary to include the means to reject talus material, so storage space within the dredge could be reserved for the fragmented material.

**Laboratory Tests**

During the year previous to the Bureau dredge tests, about 110 kg (250 lb) of samples of crust and substrate collected in the Hawaiian Archipelago had been obtained by the Twin Cities Research Center from the University of Hawaii. A series of petrographic, physical property, and cutting tests had been conducted on this material to provide background information for the future design of seabed mining systems [3].

The test results were used to calculate the total number of bits that would be used and the weight of the full-size dredge. The dredge was designed to cut a nominal 2.54 cm (1 in) deep in crust material, and the cutting force was not to exceed 18,000 N (4,000 lb). Limiting the cutting force to these values would keep the total pull on the cable at the surface below the safe working load for the 12-mm (1/2-in) cable.

The cutting force for an individual cutter was calculated by taking the mean of the average cutting forces at the 2.54-cm (1-in) depth of cut.
for both dependent cuts (those that interact with adjacent cuts) and independent cuts. This gave a value of approximately 1,000 N (220 lb) per bit and with a total pull force of 18,000 N (4,000 lb) available, up to 18 cutters could be used. To allow for cutting deeper than 2.54 cm (1 in) and for cutting in harder substrates, the maximum number of cutters was limited to 11. Once the maximum number of cutters was specified and the normal force for cutting in harder substrates, the maximum number of cutters was limited to 11. Once the maximum number of cutters was specified and the normal force per bit; hence, 11 bits would require 4,400 N (1,000 lb). Again, to allow for deeper cuts and harder substrates, a total force of 11,000 N (2,500 lb) was made available to the bits. Because of the two points of contact of the dredge body on the bottom and the location of the center of gravity, a total dredge weight of 3,000 kg (6,600 lb) was required to supply this force. Finally, the largest values of both the peak cutting force and normal force were used to design the strength of the bit holders and bit support structure of the dredge.

From the information obtained from these test series, it was determined that the cobalt-rich manganese crust responded to cutting in a manner similar to a soft to medium-hard coal [3]. This finding was opportune because the Bureau project personnel have extensive experience with coal cutting technology. Most coal cutting machines employ a tungsten carbide-tipped steel drag bit with either a radial or conical shape. For the Bureau dredges, the radial configuration was selected, and the design effort was then focused on incorporating these bits into an efficient cutting system.

Simulated Dredge Tests

The cutting system had to meet two primary requirements: (1) It had to have the ability to cut both crust and substrate material with the smallest possible cutting force, and (2) it had to have the ability to move the cuttings back up into the dredge body.

To test a variety of system designs quickly, a half-scale cutting system tester was constructed (fig. 2). This tester was a sled-like affair that allowed different cutting systems to be attached. The test sled weighed 1,760 kg (3,500 lb) fully loaded and was pulled across a simulated crust surface by a tractor. A load cell was used to measure the pulling force, which was recorded on a strip chart for later analysis. The test speed was 15 to 30 cm/sec (6 to 12 in/sec), and the length of each test was 1.2 to 2.4 m (4 to 8 ft), or until a steady state condition was reached.

All cutting system tests were conducted in a simulated crust material composed of a low-strength gypsum-based plaster. To verify that the cuttability of this material was similar to that of manganese crust, several single-bit cutting tests were conducted. The cutting forces were found to compare reasonably well with those obtained in real crust with the same cutter. A total of 35 m (120 ft) of 61-cm (2-ft) wide test beds were constructed for the tests. The plaster was simply poured into forms and allowed to dry, which gave a local relief of approximately 2.5 to 5 cm (1 to 2 in).

The cutting systems tested were made up of five tungsten carbide-tipped drag cutters, spaced 1.5 to 3.8 cm (0.6 to 1.5 in) apart, and welded to a steel plate. This cut a path about 18 cm (7 in) wide and 1.3 to 2.5 cm (1/2 to 1 in) deep in the simulated crust. Three major cutting designs were investigated: the forward V-shape, the reverse V-shape, and the straight edge. The test results show the forward V-shape with a ramp mount to be the optimum design for both cutting and picking up the cut material. The final cutter array design can be seen in figure 3. This cutter design required an average pull force of 5,560 N (1,250 lb) while achieving an average depth of cut of 2.5 cm (1 in). The tests proved that this design with ramp-mounted bits was very efficient in moving the cuttings up and back into the sample storage basket.

Target Deposit Assumptions

Based on sketchy information from previous surveys, it was known that the seabed topography in the area of interest near Johnston Island has a bottom depth ranging from 800 m to 2400 m (2,600 ft to 7,900 ft). Cobalt-rich, manganese crust deposits of varying thickness up to 9 cm (3.5 in) were known to exist on the flanks of seamounts. An average crust thickness of 2.5 cm (1 in) was assumed by Clark [2]. A further assumption was made that the maximum slope on the flanks of the seamounts was 20°, and the local relief was ± 1 m (+3 ft).

FINAL DESIGN DETERMINATION

Based on the target deposit assumptions and data obtained from the laboratory and simulated dredge tests, the overall sample dredge design was established. The concept selected was a planer-type of cutting system with the forward V-shaped cutter array developed during the simulated dredge tests.

Cutting System

Identical V-shaped cutter arrays were mounted on the top and bottom of the dredge, so dredge roll-over would not be a problem. The depth of cut could be adjusted from 0 to 10 cm (0 to 4 in) using depth-limiting skis which can be seen in figure 3. A 30- by 45-cm (12- by 18-in) opening in front of the cutting edge accepted the cuttings while rejecting talus.

The width of the V-shaped cutter array was 18 in. This required a total of 11 individual cutters, which were bolted to the dredge.
Hangup Protection

To guard against the possibility of the dredge hanging up behind or between projections, the triangular yoke on the leading edge consisted of a solid wedge that was intended to act like a sled and ride over obstructions.

Cable Protection

As stated earlier, it was deemed necessary to limit cable tension to approximately 89,000 N (20,000 lb) to avoid irreversible stretch. It was estimated that the maximum pull on the cable would not exceed 53,400 N (12,000 lb) under normal cutting conditions. This was calculated by adding the forces required to cut the crust, to overcome the friction of the dredge body on the bottom, to lift the dredge weight upslope, and to overcome the hydrodynamic drag forces acting on the cable and dredge.

However, to protect the main cable in the event of a major hangup, a "weak link" was inserted where the cable attaches to the yoke. This link was designed to fail at approximately 71,000 N (16,000 lb). If this link failed, the auxiliary bridle would break away from its stored position on one side of the dredge. Continued pull on the cable would then upend the dredge and transfer the pull to the dredge body, hopefully pulling the dredge free of the obstruction.

Fabrication of Sampling Dredges

As stated previously, the fabrication of the dredges had to proceed at an accelerated rate, because the originally scheduled January 1987 sailing date was moved up to late November 1986 to meet vessel scheduling requirements. Consequently the project personnel had to forego the planned comprehensive program of mathematical modeling and on-land testing and proceed with fabrication based on original concepts.

The primary dredge (fig. 3) had a shipping weight of 3,000 kg (6,600 lb). Its overall dimensions were 1.5 m wide by 2.4 m long by 0.5 m high (5 ft wide by 8 ft long by 1 1/2 ft high). In order to establish the center of gravity in front of the cutters, sections of welded steel plates were stacked in the forward part of the dredge's interior. The result was a rather unbalanced appearance when the dredge was moved with a forklift.

At the time that the primary dredge was nearing completion, it became obvious that there was insufficient time remaining to fabricate an identical backup unit. Fortunately, a prototype unit intended for dry land testing had been partially fabricated and then abandoned earlier in the program. When the sailing date was moved up, the plans for dry land testing were shelved and the prototype left unfinished. As time became short, the prototype was resurrected and rushed to completion. At 1,600 kg (3,500 lb) and overall dimensions of 1.2 m wide by 2.3 m long by 0.4 m high (4 ft wide by 7 ft long by 14 in high), the backup unit was somewhat smaller than the primary, but the design concept was essentially the same and the cutting system identical. Both dredges were airfreighted to Honolulu and loaded on board the Farnella in time for the November 28 departure.

Seabed Testing

As stated earlier, the primary purpose of the cruise was to obtain at least 4.5 mt (5 st) of crust and substrate samples for the Bureau of Mines Salt Lake City Research Center. There was also an agreement with the Japan Resources Association, through the Japanese Government, to test two of their dredges and provide them with 0.9 to 1.8 mt (1 to 2 st) of sample material. A representative of this organization, along with one from the Geological Survey of Japan, was on board to oversee their tests.

The bulk crust sample was collected at the Karin Ridge and Johnston Island Sites using the USGS chain-bag dredges. These dredges worked well in the rugged seabed terrain, the bulk sample being composed of about 17 pct talus material and 83 pct fragmented in situ rock, which was approximately 20 pct crust.

During a dredging run, early in the cruise, the wire rope slipped off the outboard sheave of the geophysical crane. This incident and space handling limitations prompted the decision to deploy the lighter Bureau dredge (fig. 4).

The Johnston Island Site was selected for the test of the Bureau system on December 3 because a bathymetric survey conducted previously had indicated that this probably would be the flattest seabed terrain to be encountered on the cruise. Spotting the dredge precisely at predetermined coordinates was a problem with the intermittent satellite navigation, the wind, and the current. As a result, the sea bottom where the dredge landed was extremely rugged.

Unlike the USGS chain-bag dredges and the Japanese dredges, the Bureau dredges rely on weight for bit penetration into the seabed crust. In order to maximize the weight on the cutters, the wire-out-to-depth ratio was increased to 1.6 from the typical 1.3. A 1,500-N (350-lbf) bite above the steady tension of 23,600 N (5,300 lbf) marked the start of cutting. During the next 8 min, the cable tension peaked between 10,700 and 45,000 N (2,400 and 10,100 lbf) in seven distinct bites.

The dredge ran on bottom for approximately 240 m (800 ft) during an 8-minute interval. The unit then hung up on the rough seafloor. It was pulled free and hoisted on deck. Scour marks on the top and bottom of the dredge indicated it had turned over at least once. About 30 kg (65 lb) of fractured crust and basalt substrate (about 50 pct of each) was contained in the chip basket (fig. 5). The mean size sample was about 50 mm by 30 mm by 12 mm (2 by 1.2 by 0.5 in), the largest dimension was 200 mm (8 in), and the thickest was 90 mm (3.5 in).
Redeployment of the dredge for additional runs was not attempted later in the cruise because of adverse sea conditions and safety of the crew.

CONCLUSIONS

The project personnel drew the following conclusions from the results of the seabed testing of the Bureau of Mines dredge:

1. The Bureau dredge cut crust continuously, even though it was cutting for short periods of time. The cutting concept using an array of coal-cutting bits is valid for fragmenting competent crust deposits, provided that the overall dredge design maintains the cutters in relatively continual contact with the crust surface. However, cable tension did change radically, probably indicating the terrain was too rough for continuous cutter contact and movement. The irregular movement could account for possible cuttings loss through the opening in front of the cutters as the dredge tilted forward, since the interior of the dredge did not have baffles.

2. The Bureau design lacks the versatility to negotiate rough seabed topography. Although flat deposits exist and probably could be located with appropriate instrumentation and procedures, the need exists for a system that can fragment and collect crust samples over a wide range of seabed topographies. Future seabed mining will involve areas of both rough and smooth topography, and each will need to be sampled.

3. In addition to the ability to sample in situ crust, a sample dredge should also be capable of accepting or rejecting loose talus material according to the needs of the operators.

4. The next generation of sampling dredges should be considerably lighter than those built by the Bureau of Mines. Even the lighter backup dredge strained the capabilities of the ship's winch system.

RECOMMENDATION FOR NEXT GENERATION DREDGE DESIGN

The important criteria for a reserve assessment sampler follow:

1. The ability to sample continuously in some meaningful prescribed pattern
2. The ability to follow the microtopography
3. The ability to retain cuttings once they are collected
4. The ability to be handled relatively easily on a small vessel.

The observed "bites" of the conventional chain-bag dredges and the Bureau dredge are of concern. These "bites" indicate the dredges are not sampling continuously. A small dredge cutting continuously should be able to sample at a rate of at least 10 times the average chain-bag rate of 175 kg/km (700 lb/mi). Continuous cutting would keep the wire rope in significant tension with small fluctuations in comparison with the "bites." This issue of discontinuous cutting has to be examined further in the development of a sampling system for mining.

The ability of the dredge to follow the microtopography is of great importance when considering continuous cutting. The rigidity and size of the Bureau dredge pose significant handicaps in rough terrain, such as the sampling sites of the November 1986 cruise. An articulated body of some sort would increase the dredge's ability to follow seabed contours. However, articulation complicates the problem of providing the necessary normal force required for crust cutting; that is, the weight would be distributed over more contact points than with the rigid design. The chain-bag dredge is a simple design that has articulation. The rigid frame can assume any angle of inclination with respect to the dragging bag, and the circular shape allows the dredge to roll down slope without adverse effects. Perhaps a hybrid of the chain-bag could be developed that provides sufficient normal force to cutters mounted on the leading edge of the frame.

The size and weight of the dredge is critical for safe deployment, recovery, and on-deck handling. The size and weight of the Bureau dredge presented handling problems that must be addressed in future designs.

Considering the criteria for a mine site sampler, the chain-bag dredge has several positive features and a few drawbacks. Thus, it would be a good candidate for modification to a crust cutting dredge. A cutting depth limiter could be employed; cutters could be mounted on the leading edge; and weight could be maximized where required for cutting and minimized elsewhere. Figure 6 shows one concept of a hybrid chain-bag dredge with a weighted front end.

REFERENCES


