The Potential Cost of Deep Ocean Mining Environmental Regulation

JOHN E. FLIPSE
Ocean Engineering Program
Civil Engineering Department

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John E. Flipse

Ocean Engineering Program
Civil Engineering Department
Texas A&M University
College Station, Texas 77843

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ABSTRACT

The major potential environmental threats posed by the at-sea aspects of Deep Ocean Mining are benthic and surface plumes produced by the dredging process. Engineering analysis of these plumes, their formation and dispersion, resulted in several concepts to limit to acceptable levels possible ecological impacts. The financial penalties, capital and operating costs, of applying these concepts were estimated.

Several environmental regulations requiring application of the foregoing concepts were postulated, and the impact of their capital and operating costs were evaluated in the context of the Deep Ocean Mining Cost Model developed at the Massachusetts Institute of Technology (MIT) for the National Oceanic and Atmospheric Administration (NOAA). The effect on the model's rate of return on investment for an ocean mining company to conform to the postulated regulations was found to be negligible.

In view of these findings, modification of the MIT Cost Model to accommodate secondary environmental cost impacts was deemed unnecessary. The model is well equipped to handle the primary capital, operating and delay costs which make up the significant at-sea mining system impacts, if any, of environmental mitigation.

I. INTRODUCTION

The stimulus for this research was twofold:

- What are the real environmental threats of deep ocean mining?
- What are the financial penalties for mining the deep ocean in an environmentally sound manner?

The researchers and the sponsor agreed that an effective approach would include postulating hypothetical regulations based on a realistic mining scenario. The insights provided by the extensive Deep Ocean Mining Environmental Study (DOMES) research program were to be fully considered and the DOMES system test monitoring results would provide the "problem statements" for the development of mitigation means. Although obviously not needed for early application, regulations resulting in specific hardware items were needed for the development of feasible (although not universal) engineering approaches and capital and operating cost estimates. Future regulations are likely to involve performance standards which will permit industry to exercise their considerable ingenuity.

A. Objectives

In mid-1978 an unsolicited proposal was made to the Marine Minerals Division of the National Oceanic and Atmospheric Administration's (NOAA) Office of Policy and Planning to evaluate the cost of environmental regulation of the developing deep-ocean mining inudstry. The proposal was multiphased (for budget and other reasons) and included the following objectives:

1. To postulate representative environmental regulations, and their variations, which could impact capital and/or operating costs.
2. To determine, through engineering analyses, technological changes needed in the at-sea sector of the mining system developed in the MIT model (Ref. 51) to make it conform to the postulated regulations.
3. To estimate, through parametric engineering procedures, the potential capital, operating, delay and secondary costs caused by said changes.
4. To develop a program module for the MIT cost model that would swiftly and accurately input these data.
5. To test the model and data to determine the sensitivity of the Internal Rate of Return (I.R.O.R.) to such environmental regulations.

The first three objectives are covered by this report.

During the calendar year following the proposal submittal, several significant developments in deep ocean mining have occurred:

1. Two major at-sea, one-fifth-scale, system tests were completed and monitored by NOAA under the Deep Ocean Mining Environmental Study (DOMES) and a preliminary report on one test was made available to this investigator.
2. A workshop was held by NOAA in April 1979, at which the findings of the DOMES investigations were discussed in depth. In addition, the at-sea monitoring results were discussed with excellent concurrence on environmental significance.

3. The definition of the MIT Cost Model, base-case mining system was completed with unit capital and operating costs supplied by Professor Nyhart (Ref. 51). The analysis of these data clearly indicated that cost groupings in the Model were sufficiently broad so that only very major system changes, resulting from possible environmental mitigation measures, could be identified or would be significant.

B. Modified Objectives

As no evidence of need was uncovered for major system changes to mitigate emerging environmental concerns, the analytical engineering effort was devoted to identifying and understanding mechanisms through which the mining system might effect environmental trauma and to devise means to prevent such damage. During an informal sponsor review mid-point in the research effort, tacit approval was given to the determination of the priority of environmental concerns and the development of engineering approaches for their mitigation.

Subsequent effort was devoted to determining the approximate capital and operating cost increments for applying the developed concepts to the base-case mining system of the cost model. Although the costs (in a few cases) were estimated to be as high as 1.5 million dollars, the incremental costs were insignificant in their estimated impact on I.R.O.R. for a hypothetical ocean mining company. Hence, non-specific environmental regulations (mitigation methods) were postulated to permit their realistic application to "pioneer" as well as follow-on ocean mining systems without undue financial penalty.

C. Literature Search

As stated in the introductory remarks, significant information has become available during the past year. The results of the DOMES Phase I investigations are summarized in Reference 53, a final comprehensive report. A report of the observations and measurements made during the monitoring of the Deep Ocean Mining Tests of Ocean Management, Inc., during 1978, is noted as Reference 9. This reference is an "advance copy" subject to possible modification through solicited industry inputs. The minutes covering the last major information exchange (NOAA, April 1979 Deep Ocean Mining Workshop) have been issued and provide valuable information. These are the authoritative references for this report. Nonetheless, the extensive literature generated by the DOMES program was thoroughly reviewed, and all reports on the ocean mining systems and environmental concerns associated with these systems were read. Only the pertinent reports (DOMES and others) are included in the list of references in Appendix 1.

The DOMES area, in the northeastern portion of the tropical Pacific Ocean is a rectangular area located between 5°N and 20°N latitude, and 110°W and 180°W longitude. The baseline conditions in the DOMES area have been studied and are well documented (Refs. 1, 2, 5, 6, 7, 8, 23, 27, 29, 31, and 33).

The productivity of the DOMES area has been studied by El-Sayed, et al. (Ref. 23). In their investigations, the 0.1% light level was found to lie as deep as 205 meters below the free surface, sustaining phytoplankton and other minute organism productivity at that depth, although maximum phytoplankton populations are usually found at depths less than 100 meters. They found the thermocline to vary but never exceed 100 meters, with the euphotic zone averaging about 100 meters. El-Sayed concluded that with a discharge rate of 1000 tons/day, "the change in the species composition of the phytoplankton (in the DOMES area) would not be significant."

Although quantitative studies and in-situ observations of zooplankton response to increased suspended particulate matter (SPM) had not been made, Ozturgut, et al. (Ref. 53) suggested that SPM ingestion and adsorption could cause respiratory and feeding interference, modified metabolic activity, and increased body concentrations of trace elements and compounds. Experimentation with live oceanic zooplankton is now in progress to evaluate these phenomena. In this reference, Hirota suggests "that the discharge of materials resulting from mining activities be carried out below 200 meters in order to minimize disruption to the major fraction of total zooplankton population."

At the sea bottom, substantial amounts of particulates will be resuspended by the passage of the collector. Ninety-five percent of the deep-sea animals live on or in the top centimeter of the bottom. Ignoring the mobility of some of these biota in the region of heavy burial, it is frequently assumed and generally accepted that most of the fauna is likely to be buried and killed. On the other hand, Jumars (Ref. 42) posed a series of unanswered questions on benthic sedimentation: "How many millimeters of sediment cover will prove fatal or sublethally damaging to each of the components of the benthos?; What will be the geometry and extent of the sediment blanket?; What will be the ratio of recruitment from unaffected regions of similar community structure?" To answer these questions, additional detailed investigations of the deep-sea environment during and after mining must be carried out.

II. POTENTIAL ENVIRONMENTAL IMPACTS OF DEEP OCEAN MINING

A. Description

During the past decade, international debate at the United Nations Law of the Sea Conference (U.N.L.O.S.C.) and domestic hearings on Deep Ocean Mining (D.O.M.) legislation have raised hundreds of ideas of how ocean mining could possibly impact the marine environment. Listed below, with annotations, are those that have endured the test of time, DOMES, and other scientific investigations.

1. Towed Bottom Collector

The collector on the ocean floor is expected to scour the top layer of sediment and disperse these sediments within tens of meters of the sea floor. As a "worse case" we can assume that a layer of the seabed is "shaved" off and the benthic fauna intercepted by the collector will be destroyed. Some of the sediment will be separated from the nodules near the sea floor by means of either an active or passive rejection system, and therefore add to the benthic plume while reducing the surface plume. Affected organisms will be those living on or in the first few centimeters of the seafloor.

The "worse case" collector is expected to cut a furrow estimated to be several meters wide and up to 10 cm deep, with a length estimated to be roughly 100 km/day. The biomass intercepted by the collector will be about 300 kg daily. About 5 percent of this could ascend to the surface each day and become part of the discharge plume, based on the ratio of the frontal area of the collector to the area influenced by the dredge pipe intake.

The collector winnows fine particulates from nodules in a passive way, i.e., with a rake which leads the nodules to the intakes which are located a few meters off the seabed. With the collector moving at one meter/second, the quantity of the benthic discharge of fines is about 2×10^5 grams/sec. Collector passage also redistributes interstitial water amounting to approximately 3×10^4 m^3/day with a vertical mixing height roughly equal to five times the height of the collector.

2. Benthic Turbidity Plume

A large benthic area will be affected by the deposition of resuspended clays and silts. At the sites studied in the DOMES project, maximum currents at 6 meters above the seafloor were of the order of 24 cm/sec, suggesting that local erosion and redeposition may occur from time to time. At the seafloor, currents are westerly with mean velocities less than 5 cm/sec.

The benthic plume can be expected to increase oxygen demand in the lower water column. Particulate organic matter from dead benthic biota will be suspended within the water column, and oxygen will be consumed as the organic matter undergoes bacterial decomposition or ingestion by larger invertebrates. Also, SPM may stimulate bacterial growth and oxygen consumption. However, bottom waters are well oxygenated and would withstand relatively large increases in oxygen demand.

Much of the turbidity cloud would normally be redeposited only a short distance from the collector track, with the remaining fines gradually drifting away from the collector track because of ubiquitous bottom currents. Since the little food which does reach the deep seafloor almost surely exists as a thin layer on the sediment surface, the zone of significant mortality could extend far beyond the area of mortality caused by mechanical damage or entombment alone, because of severe dilution of this meager food supply. Conversely, the food supply could be enhanced by redistribution of previously deposited, but not consumed, nutrients.

3. Pipe String Break or Leak

With expected flow velocities of approximately 5 m/sec, a major pipe string break or leak would result in the loss of delivery of nodules and sediment to the surface from the seafloor.

a. If the break or leak was below the pump or air injection location, the material in the pipe would return to the seabed without emission in the mid-depth waters. Only seawater from mid-depth would be delivered to the ship.

b. If the break or leak was above the lowest pump or air injection location, nodules would be pumped into the ocean if the pipeline and cabling remained intact.

In either event, the delivery of material to the mining ship would cease, resulting in prompt investigation of the situation. The phenomenon is therefore transient in nature and not a major source of potential environmental damage.

4. Surface Plume from Pipe Discharge

On the mining ship, the nodules are separated from the water and fines coming up the pipe, and, if discharged at the sea surface will form the surface plume. The surface discharge could consist of stray nodules, bottom and interstitial water, bottom sediment, abraded nodule fragments, and benthic biota ingested by the collector. The volume of nodules and nodule fragments unavoidably discharged was forecast in the DOMES I final report to amount to about one percent of the volume of the nodules mined. Although the OMI test reportedly lost 3.5%, such a high rate would not be tolerated in commercial operations. Due to their density, any nodules discharged will quickly pass through the surface mixed layer. The SPM is predicted to be measurable to a distance of 50-100 km from the vessel during commercial mining,with no directly discernable large scale effects beyond 100 km of the mining vessel.

The DOMES findings conclude that discharging at the surface will cause an increase in particulate concentration in the surface plume, most of which is inorganic. Ambient concentrations may also be affected by chemical exchange between discharged particulates and surface water. The visual evidence of surface discharge on the seawater is localized and difficult to detect in the far field. The discharged SPM will increase light attenuation locally. This reduction in light to subsurface waters could have profound effects upon the biota if it were to persist. However, the light attenuation decreases with increase in distance from the mining vessel, with little effect at 15 km (in the 1/5 scale pilot tests), according to the DOMES researchers.

Aside from the effects resulting from light attenuation, sediments can directly affect the behavior of organisms. Filter feeders can ingest and retain particles when feeding. Some plankton have sticky surfaces which can trap minute particles. When these protozoans are eaten by larger crustaceans, the attached particles of sediment also are ingested. The ingestion of SPM by zooplankton also could result in modified metabolic activity, along with respiratory surfaces and feeding appendages clogged by sediments.

B. Evaluation

The investigators, directed by the research contract to study the MIT Cost Model mining system, concur with the DOMES II Workshop report (Ref. 21) that "The mining systems involved will gather nodules from the sea floor by a towed collection device and transport the nodules through a pipe to a surface mining vessel. In addition to nodules, bottom water, sediments, and benthic biota will be transported in the pipe and these will be discharged into the surface water after separation of the nodules. The collector on the ocean floor is expected to scour the top layer of sediment and will discard most of these sediments within tens of meters of the ocean floor, thereby creating a benthic plume."

The above quotation accurately describes the M.I.T. Cost Model mining system and therefore justifies the application of the findings of the reference to the determination of significant environmental concerns in the current research. The result is the selection of the benthic and surface discharge plumes as the only areas of environmental concern requiring conceptual engineering solutions and parametric pricing.

Before progressing to the analysis of these phenomena, let us discuss briefly other possibilities and the reasons they were eliminated from further consideration. A major class of potentially polluting events can result from failure of components of the dredging system. A failure of the collecting device would result in "no nodules" or the ingestion of large quantities of seabed sediment. Both events are of great economic significance to the ocean miner and hence will be corrected as promptly as possible.

Similarly, a failure of the dredge pipe would result in "no nodules" and a significant delay in production, with economic penalties to the miner. In the case of pipe failure, the amount of discharge at pollution-sensitive depths would be minute because accidental discharge volumes are proportional to depth below the surface. If "total elapsed time" is considered, any failure of dredging system components must reduce pollution below already acceptable levels because of the small discharge quantities and large time spans.

Another potential environmental impact that was considered was the "topping off" of the transport vessel when transferring ore from the mining ship. Inasmuch as the nodules are likely to be transferred in a seawater slurry, the water employed will be largely surface ocean water. After transfer to the transport, the nodules will be separated and retained while the slurry medium is discharged overboard. Assuming the initial stability of the transport is adequate, this process would be accomplished by de-watering the holds, thereby retaining any abraded nodule material resulting from the slurry transfer. As a periodic, short-duration event that uses sea-surface water, the discharge was deemed to be of minor, if any, significance as a potential pollutant. The other listed potential environmental impacts were similarly analyzed and eliminated with the exception of the benthic and surface plumes.

If there are any potential environmental impacts from the deep ocean mining of manganese nodules, they will be caused by either the benthic (seafloor) plume or the surface plume.

III. AREAS OF PRINCIPAL CONCERN

A. The Benthic Plume

1. Source

As the collecting device is towed along the seabed it reacts with the sediments in several ways:

(a) The unconsolidated sediments which make up the first centimeter or two consist of fines (sometimes called "fluff") which are easily moved by any water flow. If the flow is rapid and of high volume, these fines become dispersed in the lower water column and form a cloud. The cloud is easily transported by local currents and slow to resettle.

(b) The sediments in way of the "skis" or "runners" supporting the collecting device are rapidly consolidated with a resultant "track" of 10 to 20 cm depth. Nodules in the "track" are forced into the sediment and escape the collector, which encourages "trading-off" track width for depth to enhance pick-up efficiency.

(c) Several means may be employed to separate the embedded nodules from consolidated sediments, such as blades for "shaving" the nodules and some sediment from the seabed or tines for "picking" the nodules out of the consolidated sediments. Regardless of the technique used, either a mat or a highly variable number of "globs" of consolidated sediments are likely to be presented to the collector.

2. Quantification

The DOMES Phase I final report (Ref. 53) was used as the basis for the MIT Cost Model ocean mining system. This report included a table (page 73) presenting the estimated throughputs of the system. In the absence of better data from either the industry or the at-sea 1/5 scale system tests, we have used these data. Also, two assumptions are an essential part of the ensuing analysis: (1) The disturbed fines are widely dispersed and are slow to return to the seafloor; (2) The nodules are embedded to their semi-diameters in the consolidated sediments.

The benthic plume will therefore include the following volume per day of consolidated sediments based on the "worse case" collector:

width of collector x distance traveled each day x depth of cut x .9 (in appropriate units). The factor .9 provides for the conversion of 10 percent of the consolidated sediments to fines through the action of the means used in the collector to separate the nodules from the sediments. In the case under consideration, we have a heavy fraction (Q_H) or consolidated sediment benthic quantity of:

$$\begin{array}{lccccccc} & \text{(width)} & & \text{(depth of cut)} & & \text{(length of cut)} & & \text{(\% heavy)} \\ & & & & & \text{(km/day)} & & \\ Q_H\ (m^3/\text{day}) = & 10\ m & \times & .065\ m & \times & 10 \times 1000 & \times & .9 \end{array}$$

$$Q_H = 58{,}500 \text{ say } 60{,}000\ m^3/\text{day}$$

Both the literature and the experience of this author indicate that the unconsolidated sediments average not greater than 2 cm in thickness. In those seabed regimes where this thickness might be exceeded, the consolidated sediment fraction would be smaller in compensation, because the semi-diameter embedment of nodules is seldom exceeded. In the case under consideration we have a fine benthic sediment quantity of:

$$Q_F\ (\mathrm{m^3/day}) = \overset{\text{(width)}}{10\ \mathrm{m}} \times \overset{\text{(depth)}}{.02\ \mathrm{m}} \times \overset{\text{(length)}}{100 \times 1000} + \overset{\text{(\% of heavy)}}{.1\ Q_H} \times \overset{\text{(\% solids)}}{.2}$$

$$Q_F = 20{,}000 + 1200 = 21{,}200\ \mathrm{m^3/day}\ \text{say}\ 21{,}000\ \mathrm{m^3/day}$$

where the last factor (20%) accounts for the 80% water content of the intact heavy fraction of the consolidated sediments. This total (81,000 cu meters/day) is close to the DOMES forecast quantity of 73,000 cu meters/day.

3. Disposal

Ideally, all disturbed seabed sediments would be returned to the path of the collector to minimize burial of uncollected nodules and associated marine life in adjacent paths. In practice, it is anticipated that most of the non-fluidized heavy fraction (the 90% of the consolidated sediment "slice" from the ocean floor) will be so redeposited. In the conceptual engineering approach of the following section (V), this concept will govern. The plume or cloud containing the fines is a more complicated problem. Every effort must be made to prevent the seabed sediments from being ingested by the dredge pipe and raised to the surface, for both economic and environmental reasons. Hence, the fines should be as widely dispersed as is practical without contaminating the dredging medium. The intentional dilution of the fines should minimize benthic starvation and burial. If the fines are widely dispersed and their initial quantity limited, benthic biota environmental impact will be minimized. In the conceptual engineering approach of the following section (V), this concept will govern, second only to the redepositing of the consolidated sediment (heavy fraction) in the collector path.

4. Evaluation

We may conclude, therefore, that the heavy fraction is the most serious potential environmental risk in the benthic plume because of potential burying or smothering of seabed flora and fauna.

B. Surface Plume

1. Source

There are two possible sources for new particulate matter in the surface plume: the ingested fines (and macerated biota) from the benthic plume and abraded nodule material from the pipe transit of the nodules. Some of the material abraded from the nodules may well be entrained clay, or very fine bottom sediment, released from the pores of the nodules through abrasion. However, most of the abraded material will be small particles of the manganese and iron minerals making up the nodules. Although interstitial clay is not controllable, the miner has high incentives to minimize the wastage of his "pay-dirt".

2. Quantification

(a) Ingested Fines

The MIT Cost Model calls for a collector of 10 meters width moving at 3½ knots. If we assume that the collector, the dredge pipe and the ship all move at the same speed (a most desirable happening) it will not be 3½ knots. The 1/5 scale at-sea tests demonstrated that at speeds above 2½ knots the collector is raised from the ocean floor due to increased hydrodynamic drag on the pipe string and a marked change in the pipe string catenary. As this drag is a function of the pipe diameter and the square of the speed ($D=c_f \rho AV^2$), there is no chance that a 2-foot (+) diameter pipe will permit the collector to remain in contact with the bottom when a 9-inch diameter pipe causes the collector to "fly" at ship speeds above 2½ knots. Hence, a reasonable speed would be less than 2 knots (say 1.75 knots) resulting in a collector width of 20 meters if all other parameters defined remain the same (Ref. 53). (Note: The accuracy of the heavy fraction calculation is unaffected by this modification.)

If the collector is 20 meters wide and the box from which the dredge pipe takes suction is one meter on a side, the ingested fines cannot exceed 1/20 of the benthic fine cloud (5.0%) rather than the 1/10 used in the calculation of the surface plume entrained benthic fine fraction.

(b) Abraded Nodule

Long duration tests of pumping systems of large quantities of nodules in commercial diameter pipelines have not been conducted. Early tests of two-and three-phase flow in clear plastic pipes in the <u>near-vertical</u> attitude showed surprisingly little contact of the nodules with interior pipe surfaces. Typical recirculation tests in laboratories with severely "over-used" nodules sometimes indicated high abrasion rates, due in part to the many changes of direction required. In a 50' high by 20' wide test loop the nodules go through four 90° turns per 140 feet of transit vs. two 90° turns in 15,000' of travel or some 400 more changes in direction than in a commercial system. On the other hand, a system using in-line pumps could possibly increase abrasion leading to higher percentages of abraded nodules. The suggested value is a mere 24 cubic meters/day (Ref. 53).

Using the foregoing quantities we have a surface discharge of sediment and abraded nodules:

$Q_s = .05\ Q_F + Q_A$

Q_s = quantity of solids (in m^3/day) discharged at the surface

Q_F = quantity of fine benthic sediments

Q_A = quantity of abraded nodule (in m^3/day) discharged at the surface

$Q_s = .05 \times 21000 + 24 = 1074\ m^3/\text{day}, \text{ or } \simeq 1100\ m^3/\text{day}$

This approach yields a surface discharge, including sediment and abraded nodule, approximately three times the reported value of 394 m^3/day (Ref. 53).

In our engineering approach to minimize adverse effects on the marine environment, we will consider the 1100 m^3/day value for Q_s.

3. Evaluation

The DOMES II test program is encouraging in that the sediment cloud in the surface plume has been rather elusive with its location frequently problematic. The rapid settlement below the euphotic zone of the abraded nodule is assured by its density. Unless new data are generated in the endurance tests or final DOMES II test program, it appears that over-the-side discharge will not adversely affect the euphotic zone in terms of near-field, short-term phenomena.

The area under consideration is in the North Tropical Pacific Ocean where the variation of the seasonal thermocline is minimal. It seldom exceeds 75 meters while the euphotic zone extends to 130 meters as an extreme. Based on currently available data, over-the-side discharge of dredge water, entrained sediments and abraded nodule appear to be acceptable, from an environmental point of view. If further testing should indicate the need for greater protection of the environment, a protective measure such as sub-surface discharge at approximately 200 meters depth would be adequate to protect the euphotic zone and assure settling of the sediments *below* the thermocline.

IV. ENGINEERING APPROACHES

A. Benthic Plume

1. Description

The interaction between the collector and bottom sediments produces a benthic cloud. It is inconceivable that the collector could move along the seafloor without disturbing these sediments. The object is to prevent the heavy fraction of the benthic plume from dispersing over a wide area, and to direct the settling of the heavy fraction particles to an area where the environmental impact will be minimal, such as the path behind the collector.

To accomplish this, some minor modifications must be made to the general concept of a collector. The conceptual design of a collector is regarded as a proprietary "art" form and detailed collector designs are not available for public inspection, although some aspects of the collectors can be generalized in order to suggest modifications.

Our collector rides along on sled runners wide enough to prevent it from sinking excessively into the sediments. It requires a means to reject oversized nodules and foreign objects which, if ingested, would cause damage or clogging of the mining system. There is a cutting edge, tines, or other means which skims the upper few centimeters of the sediment and extracts the nodules. The nodules and disturbed sediment travel up a ramp, which is about thirty feet wide (a commercial collector could consist of several such modules) with a slope of not more than 20°. Tines or high-pressure water jets help the nodules up the ramp while rinsing off some of the attached sediment. At the top of the ramp the nodules fall over the ramp edge onto active, expanded metal conveyors. Two partially enclosed conveyors move toward each other and drop the nodules onto a lower inclined conveyor, which delivers them to a receiver from which the lift string vacuum pipe takes suction. This conveyor arrangement can be seen in Figure 1, a side perspective view of the collector. In our approach, the whole collector is enclosed in a tent-like cover, supported by arch-shaped trusses. The cover begins at the collector front and extends past the pipe string nodule intake. As the collector moves along at a velocity of about 1 meter/sec, most of the fine sediments will be trapped inside the tent and will be at the mercy of the accelerated flow pattern within. If the aft end of the ramp is designed properly, the heavy fraction of the entrained sediments can be directed onto the path of the collector, reducing their dispersion to a minimum, and limiting the environmental impact of the heavy fraction to the collector path. The fine particulates, with low settling velocities, will hover over the bottom and will be redeposited over a very wide area with the help of bottom currents.

2. Evaluation

Some of the suggested equipment will require additional power. The conveyors require electric motors, and the water jets require motor-driven pumps. The motors and pumps are obviously two of the more critical components of the collector system, and have significant influence on the system reliability. The collector is probably the most critical component of a manganese nodule mining system, and its reliability affects the efficiency of the entire mining operation. The recovery, repair and

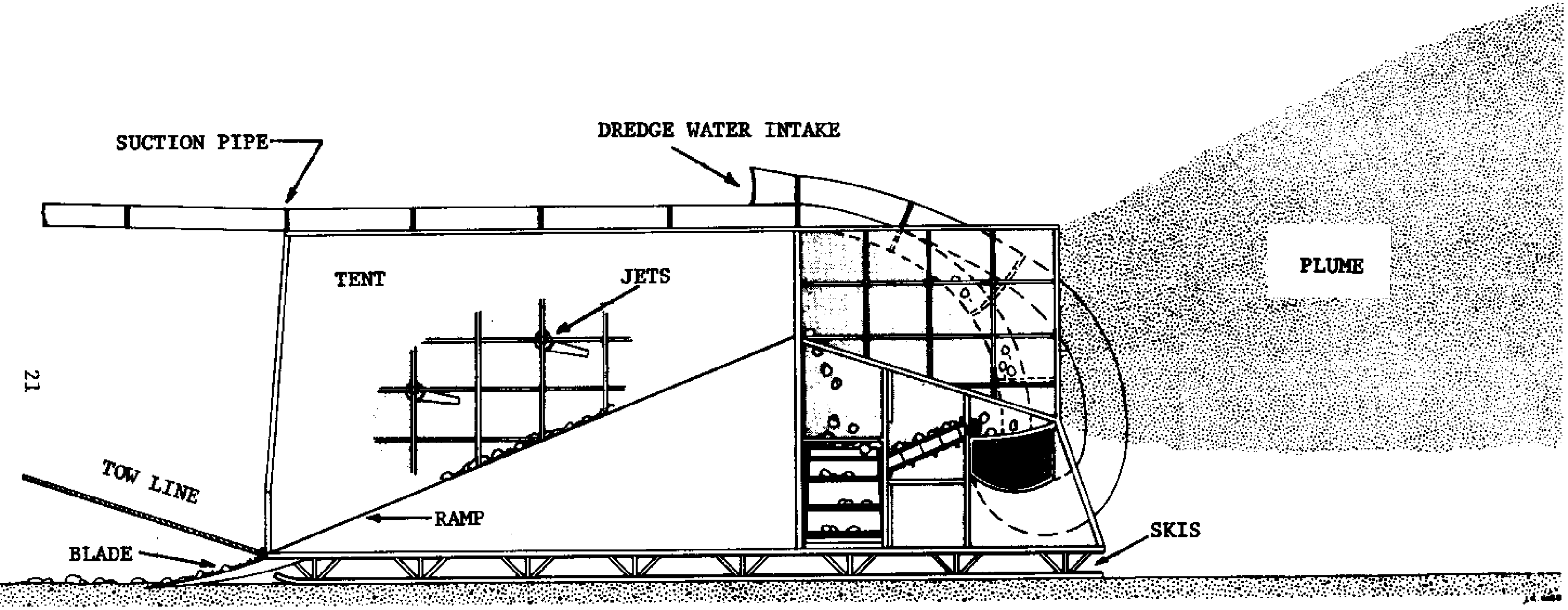

FIGURE 1. SIDE VIEW OF AN OCEAN MINING COLLECTOR

redeployment of a collector which has failed, at a nominal working depth of 5200 meters, may take more than a week.

The tent could be incorporated into the overall design with little trouble, although the hydrodynamics of the ship and the interior flow patterns would require testing. Various parameters would affect the ability of the shroud to perform properly, such as collector velocity, area ratios, and the fluid-dynamic drag of the shroud.

B. Surface Plume

1. Description

The water jets and the conveyors on the collector should separate most of the sediments from the nodules. Even if most of the sediments are kept on the bottom, nodule fragments abraded as they travel up the pipe will become part of the separator discharge and must be considered.

To avoid the surface plume problem altogether, the separator discharge could be piped down below the mixed layer and the euphotic zone. This would alleviate any surface plume, and avoids the possibility of the sediment being trapped in a divergence zone within the mixed layer. The literature suggests, and there seems to be common agreement, that such a depth would be 200 meters below the free surface.

The simplest technique for transporting the discharge from the separator to a depth of 200 meters would be the use of a flexible reinforced hose or pipe approximately two feet in diameter. A possible configuration of such a system is depicted in Figure 2. A solid pipe, conveniently installed on the ship, would transport the discharge, powered only by gravity to the hose inlet and then to a depth of 200 meters. The hose would be weighted at the bottom and/or fitted with a depressor

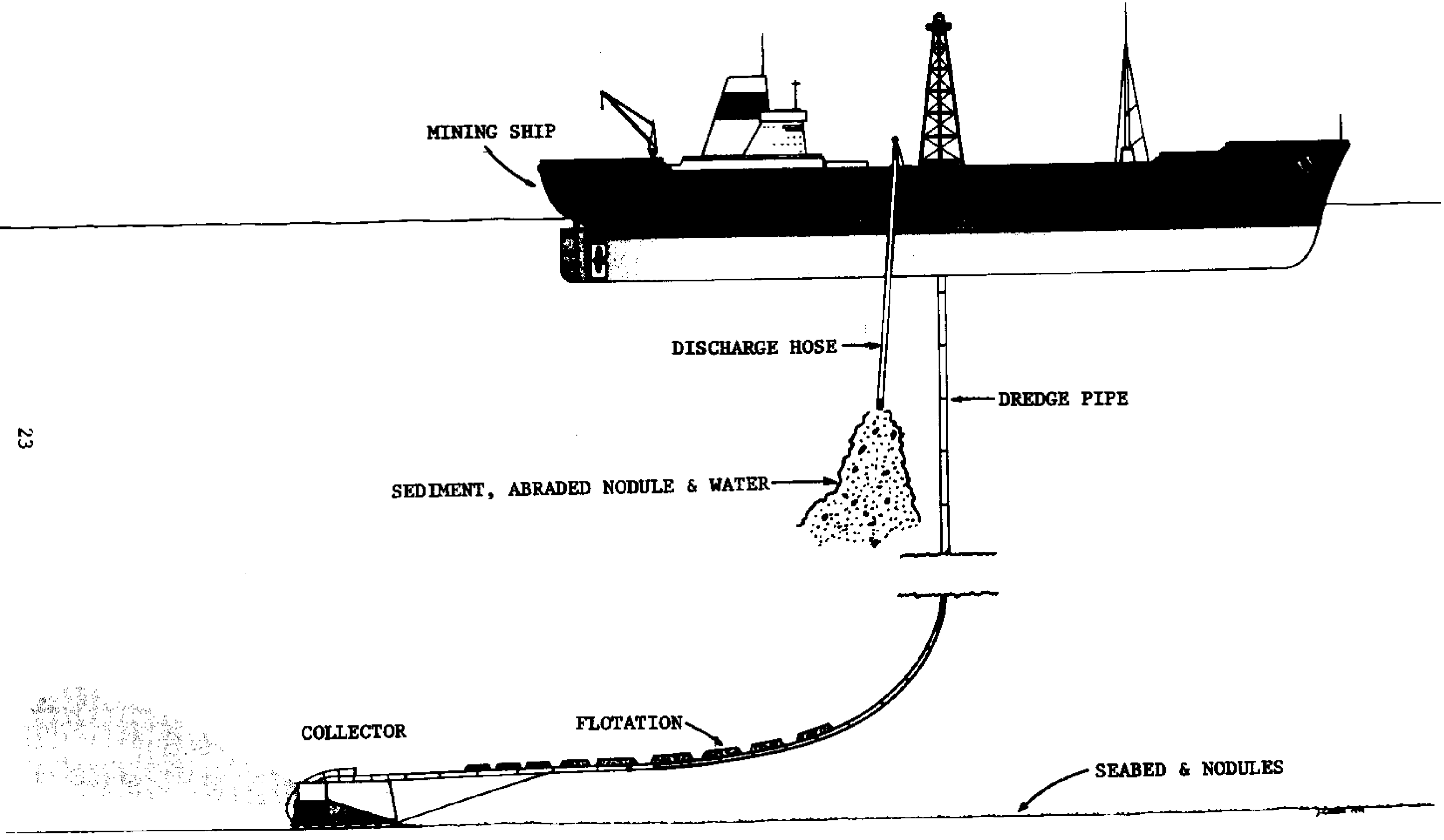

FIGURE 2. AN OCEAN MINING SYSTEM

vane to keep it as near the vertical as possible.

An extension of this concept would be to conduct the pump discharge stream to a depth of 500 meters, thereby depositing seabed water, sediments and abraded nodule material below the thermocline, pycnocline, and oxygen minimum zone into an area of extreme quiescence. The result would be an assurance that most pelagic marine biota would escape any effects and that the material would settle to the seafloor regardless of its settling rate, <u>although no currently available data supports the need for sub-surface discharge at any depth</u>.

Worth considering (and tested to some degree in a recent at-sea system test) is the use of a "settling tank" to recapture the abraded nodule material. In any system where "buffer tonnage" of nodules is retained on the mining ship, the mining ship's holds could be used. Or, separate tanks could be incorporated in the design of any system where the economic incentives justify the recapture of the abraded nodule. In either case, the mining ship overboard discharge would then consist of deep ocean water, ingested fine sediments and macerated benthic biota, and only the light constituents of the abraded nodules. The potential of this material to harm the marine environment is minimal.

2. Evaluation

Except for the uncertainty in the matter of redepositing the heavy fraction of the benthic plume (a fine area for experimentation and design development), there appear to be several alternates for handling both the benthic and surface plumes.

V. POSTULATED ENVIRONMENTAL REGULATIONS

The adversary nature of government "regulation" of industry is almost as old an American tradition as freedom itself. And, even when the parties can agree that the objectives or results of the regulation would be worthy, they are almost sure to disagree on "how much" and on the actual language of the regulation. In the interest of maintaining the dialogue between the parties until research (supported by the government) and development (by the industry) produce sufficient hard data to quantify these postulated regulations, no attempt has been made to "write" regulations. Instead, a functional description is given which can provide direction to subsequent "authors" and "critics".

A. Seabed Regulations

1. A regulation limiting the quantity of consolidated seabed sediments that can be disturbed by the nodule dislodging means of the collector.

This regulation would benefit the marine environment by minimizing: (a) sediment removal and disruption in the path of the collector, (b) quantity of sediment heavy-fraction generated, (c) quantity of sediment fine-fraction that would be redeposited near the collector path or ingested by the dredge pipe, and (d) quantity of sediment fines in the surface plume.

2. A regulation requiring a high percentage of the sediment heavy fraction to be redeposited in the collector path.

This regulation would prevent the burying of seabed biota (and, incidentally, nodules) under thick layers of heavy material, to the benefit of all.

3. A regulation requiring the removal of a high percentage of sediment from the nodules before their entry into the dredge pipe.

This regulation would reduce the amount of sediment (fines) in the surface plume.

4. A regulation requiring an increase in velocity of the stream carrying the sediment fine fraction which eludes the dredge pipe.

This regulation would assure the wide distribution of the sediment fine-fraction by seabed currents, which would prevent smothering of seabed biota.

B. Surface Regulations

1. A regulation requiring a "settling tank" to capture a high percentage of the abraded nodule or ingested sediment heavy-fraction.

This regulation would remove most of the mineral fragments from the overboard discharge and provide a high incentive to the miner to eliminate any sediment heavy-fraction from ingestion in the dredge pipe.

2.a. A regulation requiring that the overboard discharge be released to the sea 200 meters below the free surface.

This regulation would eliminate potential trauma to marine biota in the euphotic zone, all esthetic pollution, and any concern about the thermocline preventing rapid settlement of suspended particulate matter (SPM).

2.b. A regulation requiring that the overboard discharge be released to the sea 500 meters below the free surface (in lieu of 200 meters).

This regulation would deliver the discharge below the euphotic zone, the thermocline, the pycnocline and the oxygen minimum zone,precluding any possible environmental damage to the most productive volume of the water column.

VI. ESTIMATES OF COST OF REGULATION

As stated in the Introduction, cost breakdowns for the base case of the MIT Model were supplied by Professor Nyhart to assist this investigator in estimating incremental costs occasioned by postulated environmental regulations. As the engineering approaches to possible system changes to conform to the postulated regulations evolved, it became evident that even crudely estimated incremental costs were insignificant in the seabed case because: (a) the collector was not defined (structurally or by sub-systems), and (b) no cost breakdown for the collector exists, but (c) the 1976 estimated capital cost of $1.5 million and the annual replacement of the unit provide sufficient funds to incorporate any potentially mandated changes.

This is not the case for the sea surface concerns resulting in parametric cost estimates for those potentially mandated system changes. They are discussed in the following sections.

A. Seabed Regulations

Regulation 1. No incremental cost.

The less sediment "shaving", "picking", or "washing", the lower the energy costs. An area of economic incentive for the miner. (Also, see above)

Regulation 2. No incremental cost.

A matter of structural configuration of the collector with judicious placement of conveyors and means to achieve sudden changes of direction of the nodules in their movement from the seabed to the dredge pipe. Again, an area of economic incentive for the miner. (Also, see above)

Regulation 3. No incremental cost.

Some "washing" power may be required, but this cost should be offset by not lifting the tons of sediment from the seabed to the surface. The miner continues to have an incentive. (Also, see above)

Regulation 4. No incremental cost.

This regulation is based on this engineer's assessment that widely dispersed fine-fraction sediments will do less harm to the seabed (biota, nodules, etc.) than a heavier layer, which might cause suffocation and food source dilution, over a smaller area. The settling rate of the fine-fraction is very low compared to ocean currents near the sea floor. Hence, the upward or outward acceleration of this SPM should result in its wide (and, hopefully, harmless) dispersion. While there is no apparent energy trade-off, the cost of the means to accomplish this objective is minor.

B. Surface Regulations

Regulation 1. Cost $.2 to .5 million.

A logical approach to the separation of the abraded nodule material (and other high density SPM) is by "settling" these materials to the bottom sector of a tall vertical tank while discharging to the sea the dredge water and the fine SPM. As the nodule fines contain significant metal values, the miner has a high incentive to capture them in as uncontaminated a form as possible. The use of a "cofferdam" space of a ship's hold (or segment thereof) is an economical way to create the tank while the ship's bilge pumps (or specially installed pumps) can effect the de-watering. Or, if designed into the ship's hull, a passive de-watering system can be accomplished by permitting the dredge water and fine SPM to "overflow" from the hold while nodules and heavy SPM is retained.

Regulation 2. Cost $.5 to .7 million.

This concept is described in section V with sketches provided.

Regulation 3. Cost $1 to $1.5 million.

Increasing the discharge depth from 200 to 500 meters introduces several design problems which were recognized but not solved. The dynamic behavior of the hose, the magnitude of the stowage reel, the magnitude of the dead weight and its behavior, and the configuration of the handling system are typical non-linear problems. So, rather than a lower unit cost (say, per meter of depth) the unit cost may increase.

C. Evaluation

An analysis of the variations tested in the MIT Cost Model (and reported therein) showed that capital cost increases of $1 to 1.5 million did not perceptibly influence the internal return on investment (IROR). In our analysis of the operating costs of the several postulated environmental regulations, we observed frequent energy and economic trade-offs (increased equipment costs offset by energy saving, and vice-versa) making incremental operating cost estimates difficult to structure and practically impossible to quantify.

In view of the current industry position that environmental regulation guidelines are "premature", we can conclude that the findings of this research are at least "timely", allowing the industry to incorporate the engineering approaches in their system designs (or superior engineering approaches of their own) and thereby minimizing first costs and avoiding retrofit costs. And, if realistic levels of the control parameters are chosen for the first generation systems, tightening of these controls for later systems can be fairly effected based on real system experience, an ideal procedure from the several points of view.

VII. CONCLUSIONS

A. Character of Deep Ocean Mining Environmental Regulation

The data, our analysis of the data, our engineering approaches to the several environmental concerns, and subsequent evaluation of the effectiveness of these concepts resulted in postulated regulations that will:

1. Disturb the minimum area and volume of seabed commensurate with mining requirements.
2. Accept the trauma to non-mobile marine biota in the actual collector path.
3. Localize the damage by redepositing as much consolidated sedimentary material as possible in disturbed areas.
4. Widely distribute the benthic plume fine fraction with commensurate benefit to (at least) the local benthic biota.
5. Limit the ingestion of seabed sediments into the dredge pipe.
6. Capture a significant part of the abraded nodule and most dredged seabed heavy-fraction sediments on the mining ship.
7. Discharge the dredged water and entrained sediments at a depth to minimize damage to the marine environment (if proven necessary).
8. Provide for reasonable, mutually derived, initial limits and controls.

9. Envision a positive learning curve with suitable adjustment of environmental goals.

B. Financial Impacts and Significance

As stated in the previous section of this report, the capital and operating costs to achieve the objectives of the postulated environmental regulations are absolutely negligible in the case of the seabed concerns. And, for the sea surface concerns, these costs also are negligible in terms of their effect on the cost model's internal return on investment to an ocean miner. Hence, we find no real economic penalty for doing deep ocean mining in an environmentally sound manner.

One caveat to the foregoing conclusion based on the personal experience of this investigator is noted. To date, there is no evidence that there will be any environmental damage from discharging the dredged water with its entrained sediment and abraded nodule material at the sea surface. And, although the cost of delivering the discharge at 200 or 500 meters below the sea surface is negligible in terms of IROR, the findings of this research should not be construed as recommending sub-surface discharge. The costs, in terms of planning, design, sub-system interfaces, space use, and real dollars could be that "last straw" which, when added to many others, could lead to the decision by an entrepreneur not to proceed with commercial deep ocean mining.

C. Continuing Effort

In view of the minor effect, if any, that good environmental practice will have on the return on investment to the ocean miner, it is obvious that modification of the MIT Cost Model to account for secondary environmental costs is unnecessary. Thus, the second and third phase of the original unsolicited research proposal should not be undertaken.

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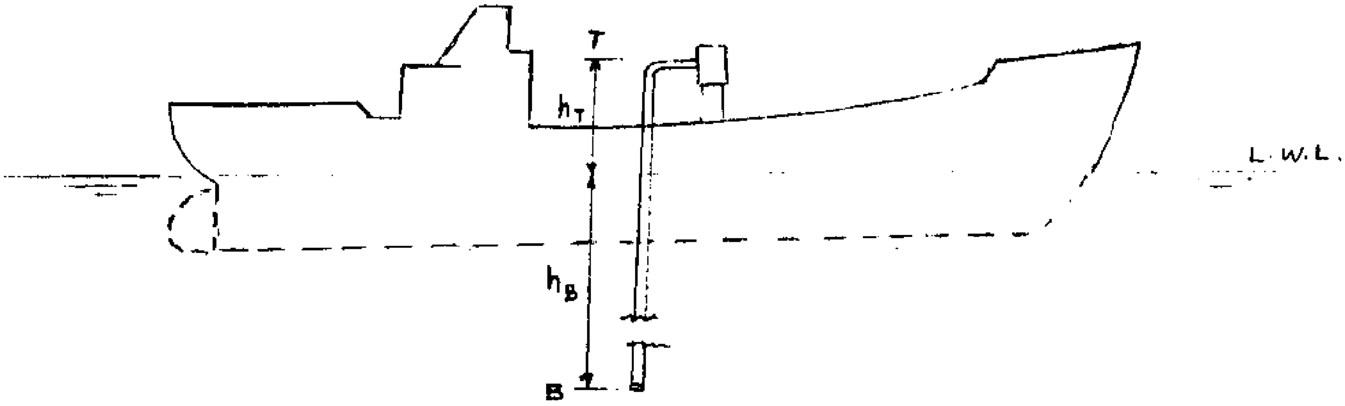
APPENDIX 2. SUPPORTING TECHNICAL CALCULATIONS

1. Velocity determination



write Bernoulli's equation between point T, point B

$$\frac{V_T^2}{2g} + \frac{P_T}{pg} + h_T - H_L = \frac{V_B^2}{2g} + \frac{P_B}{pg} - h_B$$

Assuming: $V_T = 0$

$P_T = P_{ATM}$

$P_B = P_{ATM} + pgh_B$

H_L = head loss between T, B

Plugging in, we get:

$$\frac{P_{ATM}}{pg} + h_T - H_L = \frac{V_B^2}{2g} + \frac{P_{ATM} + pgh_B}{pg} - h_B$$

$$\frac{P_{ATM} - P_{ATM}}{pg} - pgh_B + h_T + h_B - H_L = \frac{V_B^2}{2g}$$

$$\frac{V_B^2}{2g} = h_T - H_L$$

and since $H_L = f\,\frac{L}{D}\,\frac{V^2}{2g}$ and assuming $V = V_B$

$$\frac{V^2}{2g} + h_T - f\,\frac{L}{D}\,\frac{V^2}{2g}$$

$$(1 + f \frac{L}{D}) \frac{V^2}{2g} = h_T$$

$$V = \{ \frac{2gh_T}{1 + f \frac{L}{D}} \}^{\frac{1}{2}}$$

or

$$Q = \{ \frac{2gh_T \; A^2}{1 + f \frac{L}{D}} \}^{\frac{1}{2}}$$

According to Nyhart (page B9) "The slurry flow rate of the lift is equal to the sum of the flow rate of water and the flow rate of nodules."

$$Q = \frac{\pi D^2}{4} \{(1 - SF) \; V_W + SF \; V_R\}$$

where SF = solid fraction = 0.14

V_W = water velocity

V_R = nodule velocity

D = 2 ft.

$V_W = V_R + V_T = 9.86 + 3.25 = 13.11$ ft/sec

Therefore amount of water to be discharged is

$$\frac{Q}{N} = \frac{\pi(1.5)^2}{4} \quad (1 - .14) \; V_W = 1.52 \; V_W = 19.93 \text{ ft}^3\text{/sec}$$

If we assume the two foot pipe for the co-flex hose, then

$$V = 6.34 \text{ ft/sec}$$

$$N_R = \frac{(6.34) \; (2.0)}{1.28 \times 10^{-5}} = 1.0 \times 10^6$$

Assuming a smooth pipe, we get a friction factor of

$$f = 0.012$$

Now we can solve for the necessary h_T to generate this flow rate:

$$Q^2 = \frac{2gh_T\ A^2}{1 + f\ \frac{L}{D}} = \frac{2gh_T\ \pi\ D^2}{4(1 + f\ \frac{L}{D})}$$

$$h_T = Q^2 4(1 + f\ \frac{L}{D}) = \frac{(19.93)^2\ (4)\ (1 + .012\ \frac{L}{D})}{2(32.174)\ \pi\ (4.0)}$$

$$h_T = 1.96\ (1 + .012\ \frac{L}{D})$$

Try two cases

(a) $L = 200$ meters $\simeq 660$ feet

$h_T = 1.96\ (1 + .012\ (328.1)$

$h_T = 9.7$ feet

(b) $L = 500$ meters $\simeq 1640$ feet

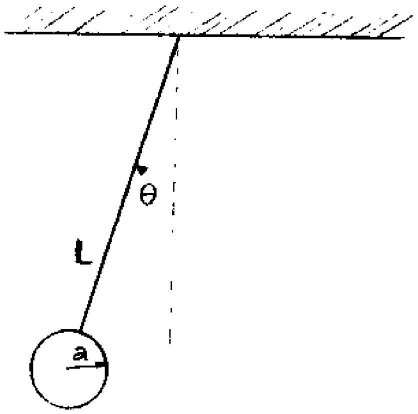
$h_T = 1.96\ (1 + .012\ (656.2)$

$h_T = 17.39$ feet

These heads are moderate and can be achieved through component design and location thereby eliminating the need for a discharge pump.

Dynamics of the Flexible Hose in Water

To determine the approximate fundamental natural frequency in water of the flexible hose system we simplify for ease in calculation. For our approximation, we assume the system is a pendulum fixed at the point of rotation oscillating with small amplitude in water.



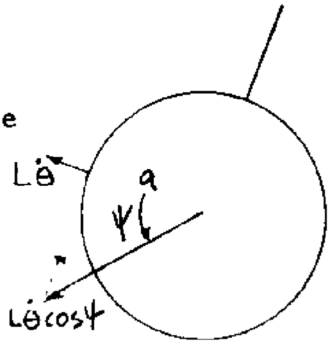
Assuming the fluid is inviscid and irrotational, we find the solution to Laplace's equation in spherical coordinates to yield the velocity potential.

$$\phi = \sum_{m=0}^{\infty} \frac{A_m(t)}{r^{m+1}} P_m (\cos \psi)$$

Where $P_m (\cos\psi)$ is the Legendre polynomials. The $A_m (t)$ are found by using the fluid structure boundary condition that the radial velocity of the pendulum is equal to the radial velocity of the fluid yielding

$$\phi = \frac{1}{2} \frac{a^3}{r^2} L \dot{\theta} \cos \psi$$

where



Now using an energy formulation we can determine the equations of motion:

Fluid Kinetic Energy is:

$$T_f = -\frac{\rho}{2} \int \int_s \phi \frac{d\phi}{dn} \, d s = \pi \frac{a^3}{3} \rho (L\dot{\theta})^2$$

Pendulum Kinetic Energy

$$T_s = \frac{1}{2} m (L\dot{\theta})^2$$

Pendulum Potential Energy:

$$V_s = mgL\ (1 - \cos\theta) \simeq \frac{1}{2}\ mgL\ \theta^2$$

Yielding the Lagrangian

$$L = T_f + T_s - V_s$$

and plugging into

$$\frac{d}{dt}\ (\frac{\partial L}{\partial \dot\theta}) - (\frac{\partial L}{\partial \theta}) = 0$$

Yields the differential equation of motion:

$$\{1 + \rho\,\frac{2}{3}\,\frac{\pi}{m}\,a^3\}\ \ddot\theta + \frac{g}{L}\,\theta = 0$$

Yielding the natural frequency:

$$\omega = \sqrt{\frac{g}{L}\ \{\frac{1}{1 + \rho\,\frac{\frac{2}{3}}{m}\,\pi\ a^3}\}} \qquad \frac{\text{rad}}{\text{sec}}$$

Showing that the natural frequency is lower in water than air since the natural frequency in air is

$$\omega = \sqrt{\frac{g}{L}}$$

let us calculate for L = 200 meters, L = 500 meters

$L = 200$ m; $\omega_n = .22$ rad/sec; $T_N = 28$ sec

$L = 500$ m; $\omega_n = .156$ rad/sec; $T_N = 40$ sec.

In water the natural frequencies would be lower and the natural periods higher.

APPENDIX 3. SUPPORTING COST CALCULATIONS

1. Postulated Surface Regulation B. = 1.:

Settling Tanks

Case 1. Alteration of an existing vessel.

Assume that two 20' x 20' x 55' settling tanks are constructed in a nodule buffer storage hold on the ship's centerline with a common centerline bulkhead. If the depth of hold is 60' (nominal), 5' is allowed as clearance for pumps, valves, etc. below the tanks.

a) Bulkhead and bottom structure required:

5 panels, 20' wide x 60' high (bulkheads) to watertight bulkhead specifications, installed against an existing bulkhead. Fabrication and installation.

2 panels, 20' x 20' (tank bottoms) to innerbottom specifications, bracketed and chocked to frames, floors and longitudinals. Fabrication and installation.

b) Dewatering equipment required:

2 sumps, sump pumps, valves, controls and piping.

2 back-flushing connections, valves and controls.

Fabrication, installation and test.

c) Nodule elevating and transfer equipment required:

2 vertical lift and 2 transfer conveyors, motors, drives and controls. Fabrication, installation and test.

d) Removals, relocation of piping and wiring, staging, clean-up and painting of the areas.

Estimated cost $500,000

Case 2. New work in a new ship-building.

Estimated cost $200,000

Case 2. Postulated Surface Regulation B-2

Discharge 200 meters below surface

Assume discharge is accomplished via a permanently installed 2' diameter steel pipe from solid-fluid separator to ship side and thence over the side below the surface to a 200 meter depth by a steel reinforced rubber composition hose. The hose would be handled by a deck crane (not provided herein) and stored on a motor-driven deck mounted reel. The hose would be fitted with a deadweight and a steel depressor vane on its lower end. The weight and vane would be housed in a deckside fitting when the hose was fully reeled in and secure.

Equipment required:

Approximately 100' of 2' I.D. low pressure steel pipe configured and welded to ship structure to suit separator location and hose overboarding equipment locations.

250 meters of 2' nominal diameter low pressure steel reinforced flexible hose.

Motor-driven reel for hose stowage, deployment and recovery. Controls and safety devices.

Deadweight and steel depressor vane with means to secure to hose terminus. Self-stowing in permanent deck-side housing.

Estimated Cost: $500,000 to $700,000

Case 3. Postulated Surface Regulation B-3

Discharge 500 meters below surface

Obviously, either 200 meters or 500 meters would be used (not both) in the event a regulation was promulgated requiring sub-surface discharge.

The physical arrangement of the components would be the same but the volume and weight of the storage reel would be considerably greater. The power requirements would also increase while the deadweight and depressor vane requirements would become severe.

Estimated Cost: $1 to 1.5 million