Chapter 5

Mining and At-Sea Processing Technologies

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Chapter 5

Mining and At-Sea Processing Technologies

INTRODUCTION

Many factors influence whether a mineral deposit can be economically mined. Among the most important are the extent and grade of a deposit; the depth of water in which the deposit is located; and ocean environment characteristics such as wave, wind, current, tide, and storm conditions. Offshore mineral deposits range from unconsolidated sedimentary material (e. g., marine placers) to consolidated material (e. g., cobalt-rich ferromanganese crusts and massive sulfides). They may occur in a variety of forms, including beds, crusts, nodules, and pavements and at all water depths. Deposits may either lie at the surface of the seabed or be buried below overburden. Some deposits may be attached solidly to nonvaluable material (as are cobalt-rich crusts), while others (gold) may lie atop bedrock or at the surface of the seabed (manganese nodules). The amount and grade of ore can vary significantly by location.

All of these variables affect the selection of a mining system for a given deposit. Dredging is the most widely used technology applicable to offshore mining. Dredging consists of the various processes by which large floating machines or dredges excavate unconsolidated material from the ocean bottom, raise it to the surface, and discharge it into a hopper, pipeline, or barge. Waste material excavated with the ore may be returned to the water body after removal of valuable minerals. Dredging techniques have long been applied to clearing sand and silt from rivers, harbors, and ship channels. Application of dredging to mining began over a century ago in rivers draining the southern New Zealand gold fields. Offshore, no minerals of any type have been commercially dredged in waters deeper than 300 feet, and very little dredge mining has occurred in water deeper than 150 feet. Offshore dredging technology is currently used to recover tin, diamonds, sea shells, and sand and gravel at several locations around the world (table 5- 1).

Some of the problems of marine mining are common to all offshore deposits. Whether one considers mining placers or cobalt-rich ferromanganese crusts, for instance, technology must be able to cope with the effects of the ocean environment—storms, waves, currents, tides, and winds. Other problems are specific to a deposit or location (e. g., the presence of ice) and hence require technology specially designed or adapted for that location.

Just as many variables influence offshore mineral processing. The processing scheme must be designed to accommodate the composition and grade of ore mined, the mineral product(s) to be recovered, and the feed size of the material. Mineral processing technology has a long history onshore. Applications offshore differ in that technology must be able to cope with the effects of vessel motion and the use of seawater for processing. Technologies currently applied to processing minerals at sea are all mechanical operations and include dewatering, sizing, and gravity separation. Processing at sea is currently limited to the separation of the bulk of the waste material from the useful minerals. This may be all the processing required for such products as sand and gravel, diamonds, and gold; however, many other products, including, for example, most heavy minerals, require further shore-based processing. Chemical treatment, smelting, and refining of metals have heretofore taken place on shore, and, given the difficulty and expense of processing beyond the bulk concentrate stage at sea, are likely to continue to be done on land in most cases.

The degree to which processing at sea is undertaken depends on economics as well as on the capabilities of technology. As with mining technology, some processing technology is relatively well developed (e. g., technology for extracting precious metals or heavy minerals from a placer) while other technology is unlikely to be refined for commercial use in the absence of economic incentives.

Table 5-1.—Offshore Mineral Mining Worldwide Commercial Operations

Location	Mineral	Water depth (feet)	Mining method	Processing	Number of mining units	Remarks
Active:						
Phuket, Thailand	Tin	100	Bucket dredging	Gravity/jigs	2	
Billiton, Indonesia	Tin	35-180	Bucket dredging	Gravity/jigs	18	
Palau Tujuh, Indonesia	Tin	150	Bucket dredging	Gravity/jigs	1	
North Sea, UK	Sand & gravel	65	Hopper dredging	Dewatering only	12	
Southwestern Africa (Namibia)	Diamonds	50-490	Water jet suction airlift	Gravity/jigs	5	Pilot plant mining
Southwestern Africa	Diamonds	0-50	Diver-held suction	Gravity/jigs	10	Very small scale
Norton Sound, Nome, Alaska	Gold	35-65	Bucket dredging	Gravity/jigs	1	Pilot mining in 1986 with Bima Motion Compensation of Bucket Ladder
Reykjavik, Iceland	**Sea** shells	130	Hopper dredge	Dewatering only	1	
Nationwide, Japan	Sand & gravel		All techs	Dewatering only	500	Small units (1,000m^3)
Bahamas	Calcium carbonate	0-35	Suction dredge	Dewatering	1	
Inactive or Terminated						
Philippines	Gold		Bucket			
Korea	Gold		Bucket			
Japan	Iron sands		Grab			
Thailand	Tin		Suction dredge			
UK	Tin		Suction dredge			

SOURCE Office of Technology Assessment, 1987

Photo credit: M.J.Cruickshank, U.S. Geological Survey

Dredge technology for offshore mining must be designed for rough water conditions.

DREDGING UNCONSOLIDATED MATERIALS

The dredge is the standard technology for excavating unconsolidated materials from the seafloor. Compacted material or even hard bedrock also can be removed by dredging, provided it has been broken in advance by explosives or by mechanical cutting methods. Dredges are mounted on floating platforms that support the excavating equipment. Mining dredges may also have equipment on board to handle and/or process ore.

Three principal dredging techniques are: bucketline, suction, and grab (table 5-2). For bucketline and suction dredging, the material is continuously removed from the seabed and lifted to the sea surface. Grab dredges also lift material to the surface, but in discrete, discontinuous quantities.

Most existing mining dredges are designed to operate in relatively protected waters. Dredge mining offshore in open water occurs in only a few countries (Southwest Africa, United Kingdom, Indonesia, Thailand). The *Bima,* a mining dredge built for tin mining offshore Indonesia, is being adapted at this time for gold mining offshore Nome, Alaska. Little special equipment capable of mining the U.S. Exclusive Economic Zone (EEZ) has yet been built, although some feasibility studies and tests have been conducted.

Bucketline or Bucket Ladder Dredging

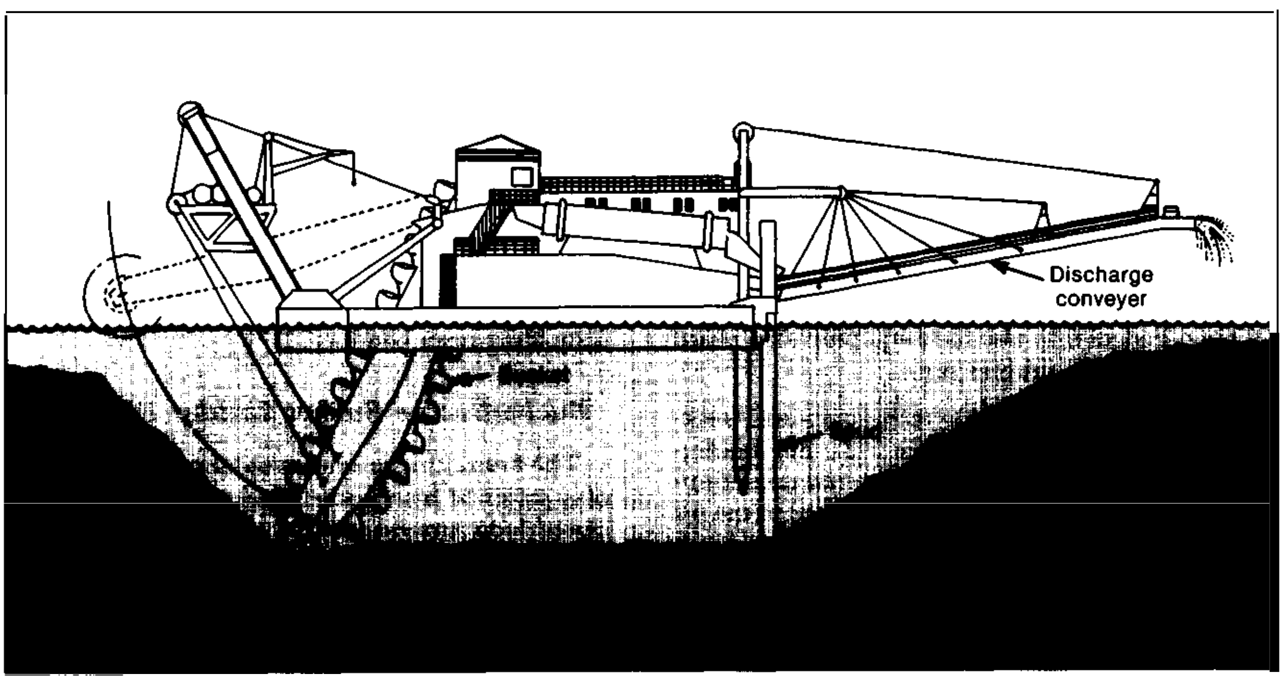
The bucketline or bucket ladder dredge consists of a series of heavy steel buckets connected in a closed loop around a massive steel ladder (in the manner of the chain on a chain saw) (figure 5-l). The ladder is suspended from a floating platform. For mining, the ladder is lowered until the buckets scrape against the dredging face, where each bucket is filled with ore as it moves forward. The buckets

Table 5-2.-Currently Available Offshore Dredging Technology

Type	Description	Present max dredging depth	Capacity
Bucketline and bucket ladder	"Continuous" line of buckets looped around digging ladder mechanically digs out the seabed and carries excavated material to floating platform.	164 feet	Largest buckets currently made are about 1.3 yd^3 and lifting rates 25 buckets per minute (1,950 yd^3/hour with full buckets).
Suction	Pump creates vacuum that draws mixture of water and seabed material up the suction line.	300 feet	Restricted by the suction distance unless the pump is submerged,
Cutter head Trailing hopper	Mechanical cutters or high pressure water jets disaggregated the seabed material; suction continuously lifts to floating platform.	50-300 feet	Many possible arrangements all based on using a dredge pump; the largest dredge pumps currently made have 48" diameter intakes and flow rates of 130 to 260 yd^3/min of mixture (10 to 20% solids).
Airlifts	Suction is created by injecting air in the suction line.	10,000 feet	Airlifts are not efficient in shallow water. There may be limitations in suction line diameter when lifting large fragments.
Grab:			
Backhoe/dipper	Mechanical digging action and lifting to surface by a stiff arm.	100 feet	Restricted by the duration of the cycle and by the size of the bucket; currently largest buckets made are 27 yd^3.
Clamshell/ dragline	Mechanical digging action and lifting to surface on flexible cables.	3,000 feet	The largest dragline buckets made are about 200 to 260 yd^3/hr; power requirements and cycle time increase with depth.

SOURCE: Office of Technology Assessment, 1987.

Figure 5-1.—Bucket Ladder Mining Dredge



The bucket ladder dredge is a proven and widely used dredge for offshore mining; however, its use to date has been limited to calm, shallow water.

SOURCE: M.J. Cruickshank, U.S. Geological Survey.

traveling up the ladder lift the material to the platform and discharge the ore into the processing plant.

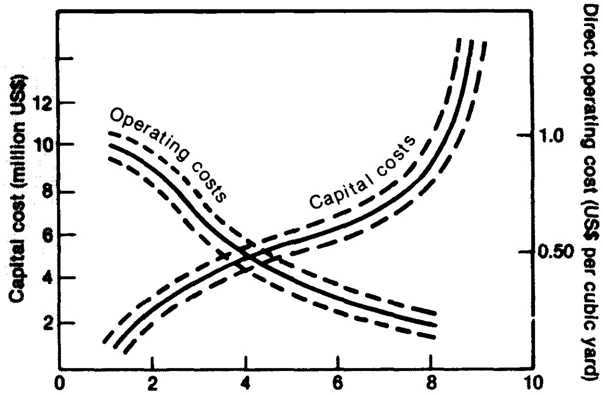
The bucket ladder dredge is the most proven and widely used technology for mining offshore tin placers in open water in Southeast Asia. Bucket ladder dredges are widely used to mine onshore gold, platinum, diamonds, tin, and rutile placers in Malaysia, Thailand, Brazil, Colombia, Sierra Leone, Ghana, New Zealand, and Alaska. Bucket ladder dredge technology is still the best method to "clean' bedrock, which is particularly important for the recovery from placer deposits of heavy, high-unit-value minerals like gold and platinum. These dredges have buckets ranging in size from 1 to 30 cubic feet. The deepest digging bucket line dredges are designed to dig up to 164 feet below the surface.

Prices of bucket ladder dredges (including processing plants) for mining onshore vary with dredge capacity (bucket size) and with dredging depth. A small bucket dredge (with 3-cubic-foot buckets) may sell for approximately $1.5 million (free on board plant). Such a dredge can mine 60,000 to 80,000 cubic yards of ore per month at depths of 30 to 40 feet below the hull. The cost of larger onshore mining bucket dredges (with buckets as large as 30 cubic feet) and capacities up to 1 million cubic yards per month may reach $10 million to $20 million, depending on digging depth and other variables.

The per-cubic-yard capital and operating costs of larger dredges are lower than those of smaller dredges (figure 5-2). Offshore bucket ladder dredges cost more than onshore dredges because they must be more self-contained. They must be built to carry a powerplant, fuel, supplies, and mined ore. The hull also must be larger and heavier to withstand waves and to meet marine insurance specifications. In 1979, the capital cost of the 30-cubic-foot *Bima* was about $33 million. Approximately 10 bucket dredges configured for offshore use are currently mining tin in Indonesia in water depths of 100 to 165 feet at distances of 20 to 30 miles offshore.

Despite their versatility, offshore uses of bucket ladder dredges are limited. Much of the EEZ around the United States is subject to waves and ocean swells that could make bucket ladder dredging difficult. To ensure that the lower end of the ladder maintains constant thrust against the cutting face, motion compensation systems must be installed. These systems are large hydraulic and air cylinders that act like springs to allow the end of the ladder to remain in the same place while the hull pitches and heaves in swells (figure 5-3). Other limitations of current dredges include the high wear rate of the excavating components (e. g., buckets, pins, rollers, **and tumblers) and the lack of mobility. Offshore bucket dredges are not self-propelled and must be towed when changing locations. For long tows across rough water, the ladder makes the vessel unseaworthy and makes towing impractical. The bucket dredge *Bima* was actually carried on a submersible lift barge from Indonesia to Alaska. In designing offshore dredges, especially those working in rough water, careful attention must be given to seaworthiness of the hull.**

Figure 5.2.—Capital and Operating Costs for Bucket Ladder Mining Dredges

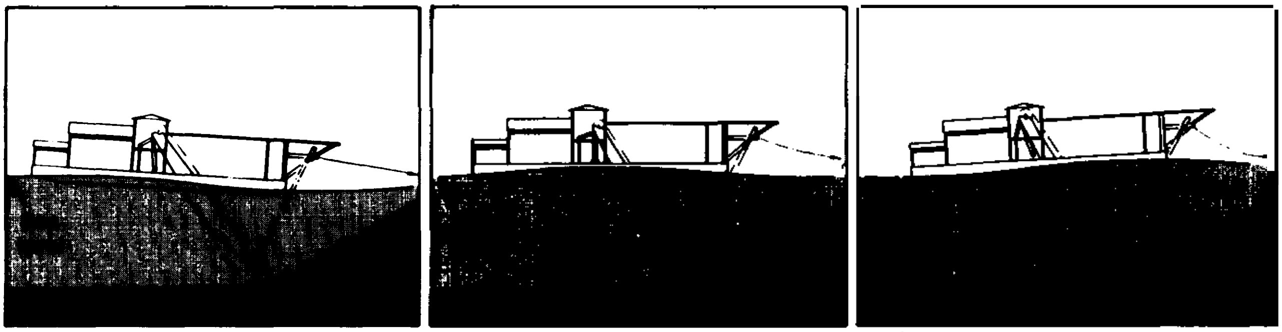


Dredges for use offshore would cost more to build and operate than the estimates illustrated here, since they would have to be self-contained and contain a power plant, fuel, supplies, and mined ore. They would also have to be capable of withstanding waves and high winds.

SOURCE: Adapted from M J. Richardson and E.E. Horton, "Technologies for Dredge Mining Minerals of the Exclusive Economic Zone," contractor report prepared for the Office of Technology Assessment, August 1986

Most bucket ladder dredges are now built outside the United States, although the capability and know-how still exist in this country. Except for the motion compensation systems installed on offshore dredges, bucket ladder dredge technology has remained essentially static, and there have been only minor gains in dredging depth in the last 50 years.

Figure 5-3.–Motion Compensation of Bucket Ladder on Offshore Mining Dredge



Motion compensation systems might be necessary offshore to ensure that the lower end of the dredge ladder maintains constant thrust against the cutting face while the dredge hull pitches and heaves in swells.

SOURCE: Dredge Technology Corp.

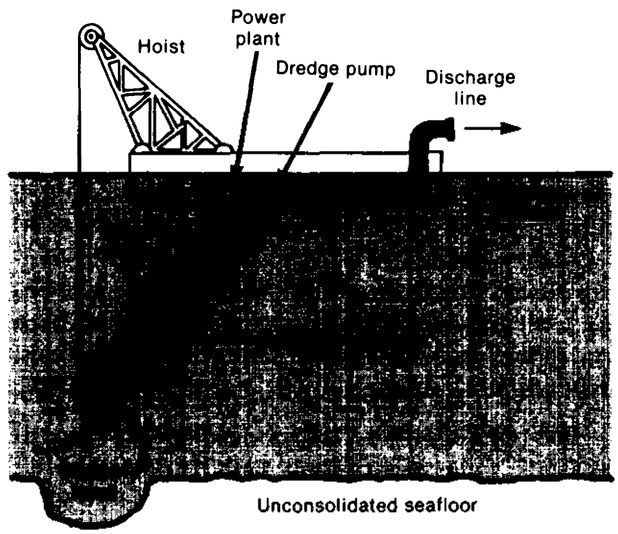
With the availability of new materials and higher strength steels, it is now possible to design bucket ladder dredges capable of digging twice as deep (330 feet) as present dredges, but the capital and operating costs would be greatly increased.

Suction Dredging

Suction dredging systems have three principal components: a suction device, a suction line, and a movable platform or vessel (figure 5-4). The suction device can be either a mechanical pump or an airlift. Pumps are most common on suction dredges; airlifts have more specialized applications. Pumps create a drop in pressure in the suction line. This pressure drop draws or sucks in a mixture of seawater and material from the vicinity of the suction head and up the suction line into the pump. After the slurry passes through the pump, it is pushed by the pump along the discharge pipe until it reaches the delivery point.

Pump technology is considered relatively advanced. Dredge pumps are a specialized application. The main features required of dredge pumps are large capacity, resistance to abrasion, and efficiency. To accommodate the large volumes of material dredged, the largest dredging pumps have intakes of up to 48 inches in diameter and impellers up to 12 feet in diameter. These parts require large steel castings that are both costly and complicated to make. The flow of solids (e. g., silicate sand or gravel) and water at speeds of 10 to 20 feet per second through the pump and suction line causes abrasion and wear.

Figure 5-4.–Components of a Suction Dredge



The main types of suction dredges currently applicable to offshore mining are hopper, cutter head, and bucket wheel dredges.

SOURCE: Office of Technology Assessment, 19S7.

Pumps create suction by reducing the pressure in suction lines below atmospheric pressure. Only 80 percent of vacuum can be achieved using present mechanical pumping technology. This constraint means that dredge pumps cannot lift pure seawater in the suction line more than about 25 feet above the ocean level. This distance would be less for a mixture of seawater and solids and would vary with the amount of entrained solids. Greater efficiency can be achieved by placing the pump below the water line of the vessel, usually as near as possible to the seabed. This placement is more costly, since the pump is either a long distance from the power source or the pump motors must be submerged. Such components are very heavy for large pump capacities. An alternative applicable for deep dredging is to use several pumps in series and boost the flow in the suction line by means of water jets. This technique has been tested and proven but is not in widespread use because it is inefficient.

The configuration of the suction head plays an important role by allowing the passage of the solids and water mixture up the suction line. In harder, more compact material, the action of the suction head may be augmented by rotary mechanical cutters, by bucket wheels, and/or by water jets, depending on the specific applications. When the material to be dredged is unhomogeneous, such as sand and gravel, the entrance of the suction line is restricted to prevent foreign objects (e. g, large boulders) from entering the suction line. The main technological constraints in suction and discharge systems are wear and reliability due to corrosion, abrasion, and metal fatigue.

The platform or vessel that supports suction dredging components must be able to lift and move the suction head from one location to another. Since most dredgeable underwater mineral deposits are more broad than thick, the dredge must have the capability to sweep large areas of the seabed. This is achieved by moving the platform, generally a floating vessel; although experimental, bottom-supported suction dredges have been built and tested.

The main types of suction dredges currently applicable to offshore mining in the EEZ are hopper, cutter head, and bucket wheel dredges.

Hopper Dredges

Hopper dredges usually are self-propelled, sea-going suction dredges equipped with a special hold or hopper in which dredged material is stored (figure 5-5). Dredging is done using one or two dredge pumps connected to trailing drag arms and suction heads. As the dredge *moves* forward, material is sucked from the seabed through the drag arms and emptied into the hopper. Alternatively, the dredge may be anchored and used to excavate a pit in the deposit.

Hopper dredges are used mainly to clear and maintain navigational channels and harbor entrances and to replenish sand-depleted beaches. In the United Kingdom and Japan, they are also used to mine sand and gravel offshore. Hopper dredges are configured to handle unconsolidated, free-flowing sedimentary material. The suction heads are usually passive, although some are equipped with high-pressure water jets to loosen seabed material. The trailing drag arms are usually equipped with motion compensation devices and gimbal joints. These devices allow the drag arms to be decoupled from vessel motion and enable the drag-heads to remain in constant contact with the seafloor while dredging.

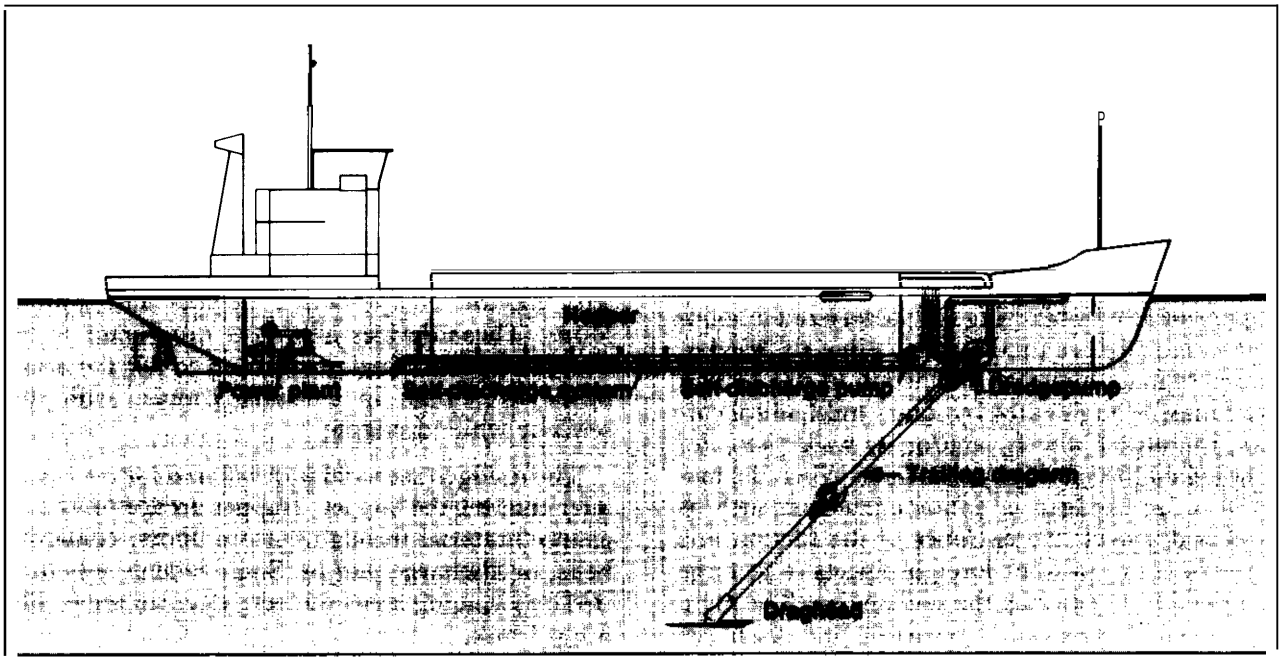
The dredged material is dewatered for transport after entering the hopper. Hopper dredges may discharge material through bottom doors, conveyor belts, or discharge pumps. Some models are emptied by swinging apart the two halves of an axially hinged hull.

Capacities of sea-going suction hopper dredges currently range from 650 to 33,000 cubic yards. Although the theoretically maximum-sized hopper dredge has not been built, the maximum capacity of present dredges is a compromise between the higher capital investment required for greater hopper capacity and the higher operating costs that would result from more trips with smaller hoppers. Typical operating depths for hopper dredges are

Photo credit: J. Williams, U.S. Geological Survey

Trailing suction hopper dredge *Sugar Island* with drag arms stowed and hopper space visible.

Figure 5-5.—Trailing Suction Hopper Dredge



Hopper dredges have been used mainly to clear and maintain navigational channels and harbor entrances and to replenish sand-depleted beaches. A hopper dredge is currently being used to mine sand and gravel in the Ambrose Channel entrance to New York Harbor.

SOURCE: Dredge Technology Corp.

between 35 and 100 feet, and 260 feet is considered the maximum achievable depth with currently available technology. For current specifications and capacities, the capital costs of hopper dredges range from $5 million to $50 million.

Except for sand and gravel mining in Japan and the North Sea, hopper dredges have not been used extensively to recover minerals. However, hopper dredges adapted for preliminary concentration (beneficiation) of heavy minerals at sea, with overboard rejection of waste solids and water, are likely candidates for mining any sizable, thin, and loosely consolidated deposits of economic heavy minerals that might be found in water less than 165 feet deep.

A stationary suction dredge, similar in principle to the anchored suction hopper dredge, has been designed and extensively tested for mining the metalliferous muds of the Red Sea.[1] Although the dredge has not been used commercially, it successfully retrieved muds in 7,200 feet of water.

Cutter Head Suction Dredges

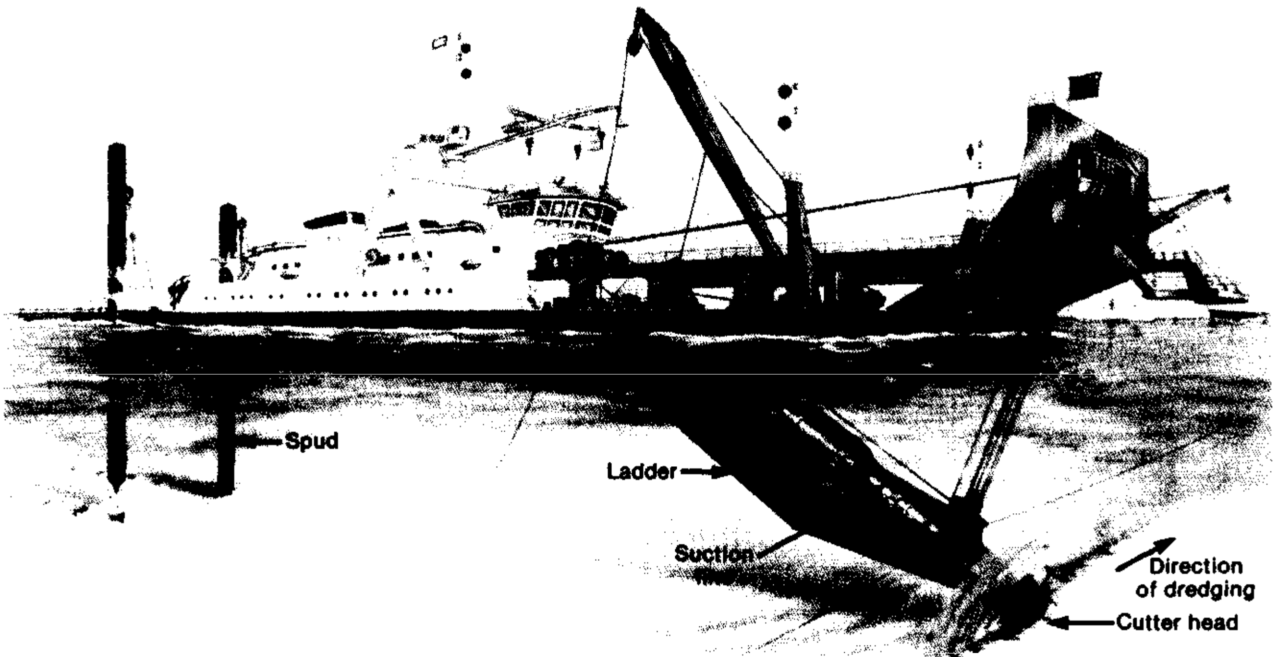
Mechanically driven cutting devices may be mounted near the intake of some suction dredges to break up compacted material such as clay, clayey sands, or gravel. The two main types are cutter heads and bucket wheels.

Cutter head dredges are equipped with a special cutter (figure 5-6) mounted at the end of the suction pipe. The cutter rotates slowly into the bottom material as the dredging platform sweeps sideways, pulling against "swing lines' anchored on either side. Cutter head dredges usually advance by lifting and swinging about their spuds when in shallow water.

Cutter head dredges are in widespread use on inland waterways for civil engineering and mining projects. Onshore, these dredges have been used to mine heavy minerals, (e. g., ilmenite, rutile, and zircon) from ancient beaches and sand dunes in the

[1] M.J. Cruickshank, "Technology for the Exploration and Exploitation of Marine Mineral Deposits, *Non-Living Marine Resources (New* York, NY: United Nations, Oceans, Economics, and Technology Branch), in press.

Figure 5.6.—Cutter Head Suction Dredge



Dredges such as this have been used at inland mine sites to mine heavy minerals such as ilmenite, rutile, and zircon.

SOURCE: Dredge Technology Corp

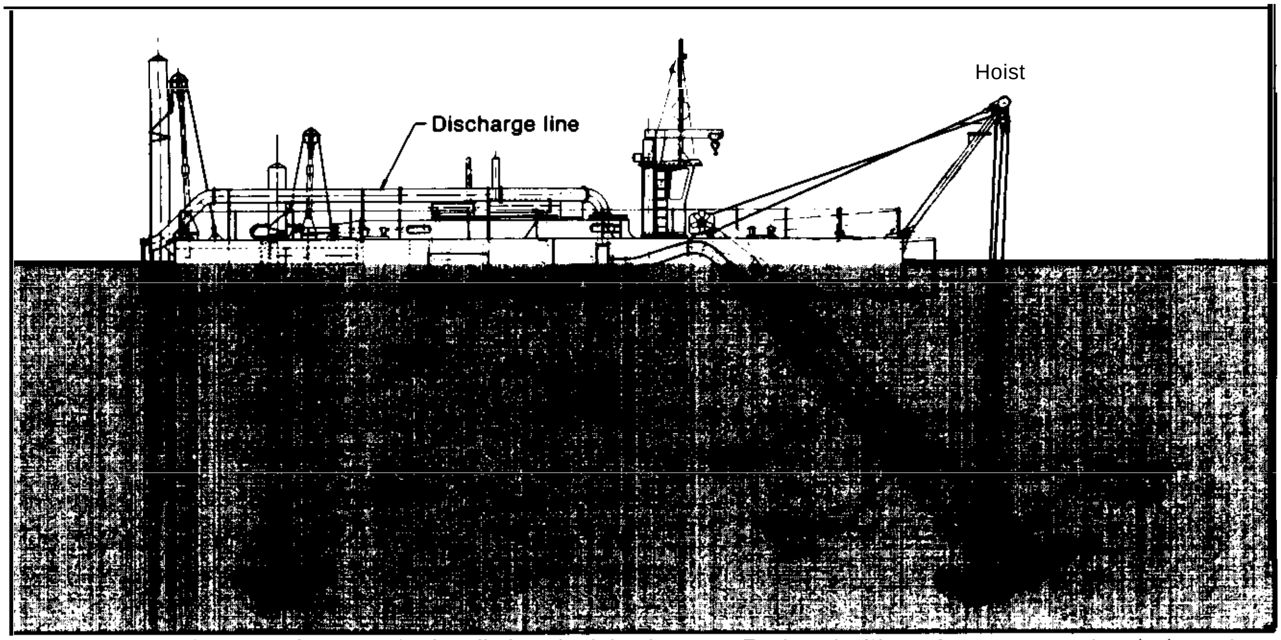
United States (Florida), Australia (Queensland), and South Africa (Richards Bay). Ore disaggregate by the cutter is pumped through a flexible pipeline to a wet concentrating plant floating several hundred feet behind the dredge. This configuration, while common on protected dredge ponds inland, may not be suitable for mining in the open water of the marine environment because of wave, current, and wind conditions.

Large self-propelled cutter head suction dredges have been built that are capable of steaming in rough water with the cutter suction ladder raised. While not able to operate in heavy seas, this type of dredge can disengage from the bottom and "ride out' storms. Adaptation of a sea-going cutter head dredge to mining may require a motion compensated ladder and installation of onboard processing facilities and would require addition of a hopper or the use of auxiliary barges.

The capital costs of cutter head suction dredges vary widely with size and configuration. For seagoing, self-powered dredges the capital costs would be similar to those of hopper dredges, i.e., up to $50 million. The capacities of cutter head dredges vary with the size of the dredge pumps, which range in diameter between 6 and 48 inches. This range of diameters corresponds to mining volumes of solids between 100 and 4,000 cubic yards per hour.

Like suction hopper dredges, the operating depths of available cutter head dredge designs are limited by dredge pump technology to between 35 and 260 feet, although greater mining depths could be achieved with incremental technical improvements. The cutter head suction dredge is not considered suitable for cleaning bedrock to recover gold or other very dense minerals in placer deposits, due to inefficiency in recovering the heavier minerals.

Figure 5-7.—Bucket Wheel Suction Dredge



Bucket wheel dredges have been used primarily in calm inland waters. Equipped with motion compensation devices, these dredges may have some potential for mining offshore placer deposits.

SOURCE: Dredge Technology Corp.

Bucket Wheel Suction Dredges

The bucket wheel dredge (figure 5-7) is a variant of a cutter head dredge, differing mainly in that the cutter is replaced by a rotating wheel equipped with buckets that cut into the dredging face in a manner similar to a bucket ladder dredge. The buckets are bottomless and discharge directly into the suction line.

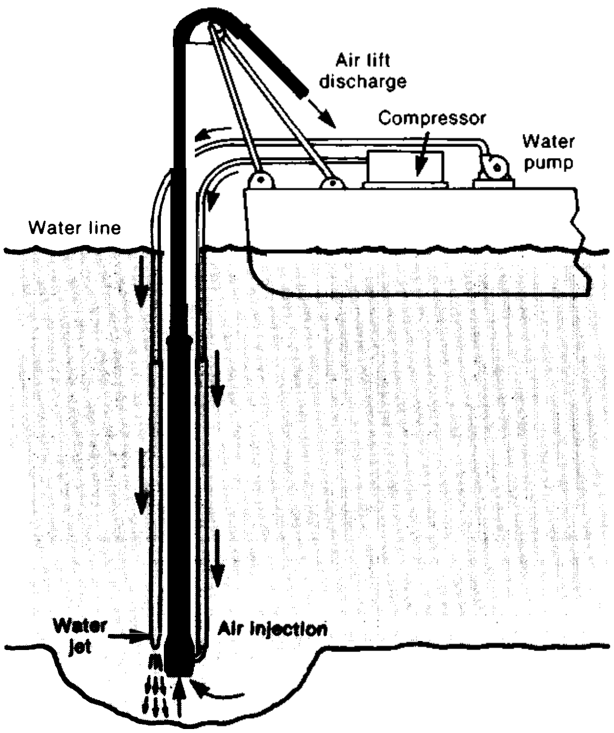
Bucket wheel mining dredges are a relatively new development and have been used primarily in calm inland waters. Some applications include tin mining in Brazil, sand and gravel mining in the United States, and heavy mineral mining in South Africa. The bucket wheel dredge has not been used in the EEZ, but it may have potential for mining offshore heavy minerals in specific applications. Motion compensation, offshore hull design, and mobility would need to be considered. These dredges are less effective when cutting clay-rich materials, which may clog the buckets, and when dredging boulders, which could block the opening into the suction lines. However, bucket wheel dredges are more suitable than cutter head suction dredges for mining heavy minerals, since the bucket wheel avoids the problem of loss of heavy minerals on the bottom.

Air Lift Suction Dredges

In airlift suction dredging, air under pressure is injected in the suction line of the dredge, substituting for the mechanical action of a dredge pump (figure 5-8) and creating suction at the intake which allows the upward transport of solids. Airlifts have been used for many years in salvage operations and, during the past 25 years, for mining diamond-bearing gravels off the southwestern coast of Africa.

The technology of airlift dredges has not reached the level of development and widespread use of the other forms of suction dredging, but the configurations are similar. Much research has been done on the physics of the flow of water, air, and solids mixtures in airlift suction dredging, because this method has been considered one of the most promising for dredging phosphorite or manganese nodules from great ocean depths. In general, applica-

Figure 5-8.—Airlift Suction Dredge Configuration



Airlift dredges may be applicable for some seabed deposits 300 feet or more below the ocean surface. Airlift dredging has been used on a pilot scale to lift manganese nodules from about 15,000 feet.

SOURCE: Office of Technology Assessment, 1987.

tions of airlifts for mining offshore minerals may be considered for depths between 300 and 16,000 feet. Suction and air delivery lines can be handled with techniques readily adapted from the petroleum industry; the problem of platform motion in response to long period waves can be overcome by adapting motion compensation systems used in the petroleum industry; and seabed material can be disaggregated at the suction intake by high-pressure water jets or by hydraulically driven mechanical cutters.

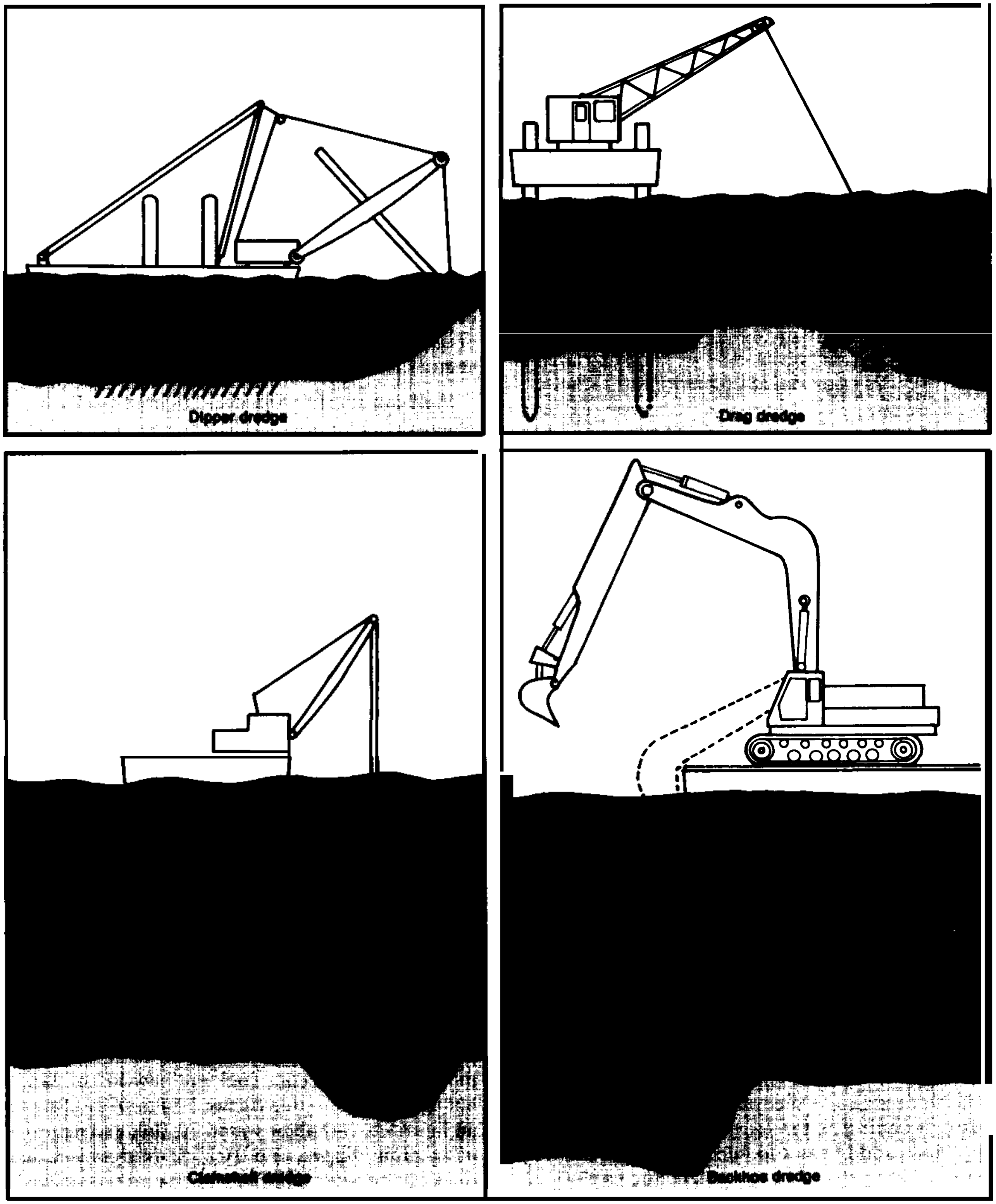
Grab Dredges

Grab dredging is the mechanical action of cutting or scooping material from the seabed in finite quantities and lifting the filled ' 'grab' container to the ocean surface. Grab dredging takes place in a cycle: lower, fill, lift, discharge, and again lower the grab bucket. Clamshell, dragline, dipper, and backhoe dredges are examples of this technology (figure 5-9). Clamshells and draglines are widely used for dredging boulders or massive rock fragments broken by explosives and for removing overburden from coal and other stratified mineral deposits. The clamshell and dragline buckets are lowered and lifted with flexible steel cables. Variants of clamshell dredging have been used in Thailand to mine tin in Phuket Harbor and in Japan to mine iron sands in Ariake Bay. In the late 1960s, Global Marine, Inc., used a clamshell dredge for pilot mining of gold-bearing material from depths of 1,000 feet near Juneau, Alaska. Variants of dragline dredges have been used since the late 19th century to recover material from the deep seafloor.

With appropriate winch configurations for handling large amounts of cable and large buckets, grab dredging is similar to the traditional technologies used to hoist material from deep underground mines (e. g., in South Africa, where it is economically feasible to hoist gold ores from 12,000 feet below the ground surface). Most aspects of clamshell dredging technology, including motion compensation for working on a moving platform at sea, have been developed and proven by either the mining or petroleum industry and are readily available for adaptation to offshore mining.

Dipper and backhoe dredges are designed for use on land (figure 5-9). They may be placed on floating pontoons for offshore dredging but are limited to shallow-water applications. Backhoes especially can be easily adapted to mining in protected shallow water. Commercial off-the-shelf backhoes with a maximum reach of about 30 feet and buckets with capacities of up to 3 cubic yards are readily available for gold or tin placer mining in protected environments. Backhoes mounted on walking platforms are conceivable for excavation in shallow surf zones. Backhoe mining is limited by depth of reach, small capacity, and the inability of the operator to see the cutting action of the bucket below water. Dipper dredges are widely used to mine stratified mineral deposits (e. g., coal and bauxite) on land, but their unique action (figure 5-9) restricts offshore applications to shallow water. As dredged material using grab, dipper, and backhoe dredges is raised through the water column, the material is washed, which may not be desirable in mining.

Figure 5-9.—Grab Dredges



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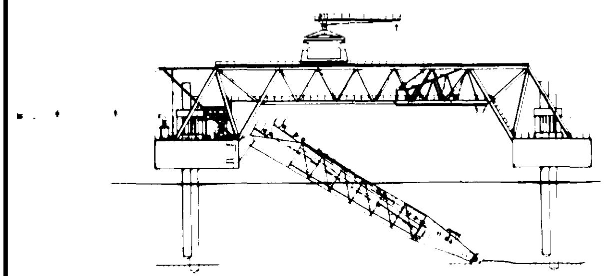
NEW DIRECTIONS AND TRENDS IN DREDGING TECHNOLOGY

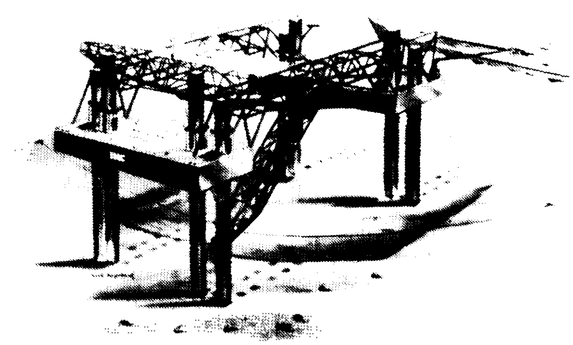
Dredge technology for offshore mining falls into two distinct categories: technology for mining nearshore in shallow, protected water; and technology for further offshore in deeper water subject to winds, currents, and ocean swell. Dredging systems for a shallow environment can be readily adapted from the various types of dredges currently used onshore. Dredges for mining in a deep-water environment must be designed with special characteristics. They must be self-powered, seaworthy platforms equipped with motion compensation systems, onboard processing plants, and mineral storage capabilities.

Design and construction of offshore dredge mining systems for almost any kind of unconsolidated mineral deposit or environment on the continental shelf are possible without major new technological developments. However, for some environments, there may be operating limitations due to seasonal wave and storm conditions. No breakthroughs comparable to the change from the piston to the jet engine in the aircraft industry, for instance, are needed. If deposits of sufficient size and richness are found, incremental improvements in dredging technology can be expected. Costs to design, build, and operate dredging equipment for offshore mining are the most significant constraints.

Several new design concepts have been developed to help solve some of the problems of dredging at sea. The motion of platforms floating on the ocean generally make dredging difficult, but there are three ways to alleviate this movement other than those described previously. In one approach for shallow water, one firm has designed and built an eight-leg "walking and dredging self-elevating platform" (WADSEP) to support a cutter head suction dredging system (figure 5-10). By raising and translating one set of legs at a time the platform creeps slowly across the seafloor. Since the platform is firmly grounded, the problem of operating in rough, open water is reduced. The dredge ladder and cutter head sweep sideways by pulling against anchors. This self-elevating platform could equally well support a bucket ladder dredging operation. The practical limit for dredging using a WADSEP is probably about 300 feet. Although the concept and technology are sound, the WADSEP is not currently cost-effective to use.

Figure 5-10.—Cutter Head Suction Dredge on Self-Elevating Walking Platform





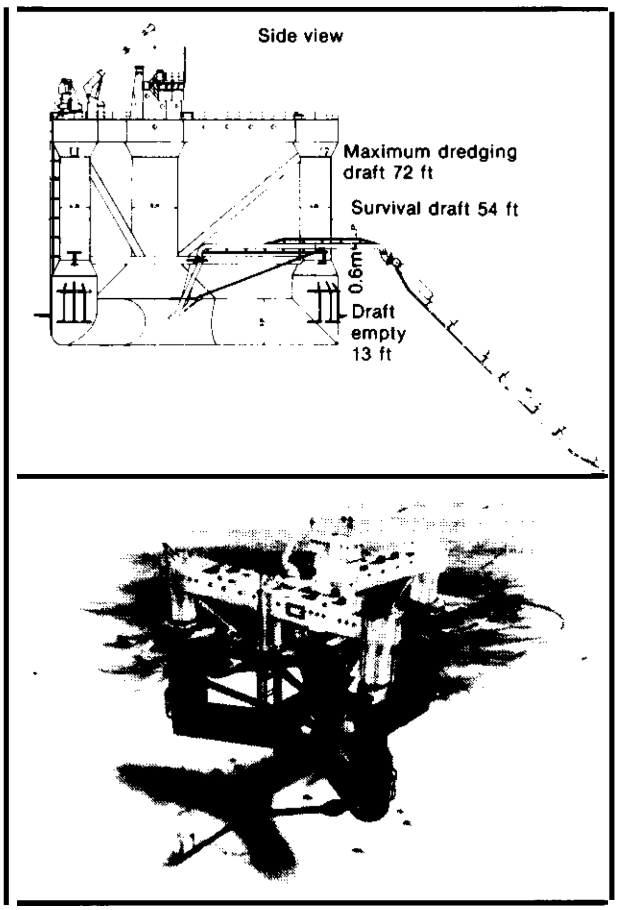
Although the technology is proven, mining operations with a self-elevating walking 'platform are currently very expensive.

SOURCE: Dredge Technology Corp.

A second technological approach to the problem of dredge motion in offshore environments is to use a semi-submersible platform, such as those in widespread use in the petroleum industry. This would enable a dredge to continue mining or to stay on-station rather than having to be demobilized during rough weather. A design for a suction dredge that incorporates a seaworthy semi-submersible hull is shown in figure 5-11. A disadvantage of the semi-submersible platform would be its sensitivity to large changes in deadweight if dredged material is stored on board.

A third approach to eliminating platform motion in shallow water is to develop a submerged dredge. This project has proved to be complex and difficult in systems tested to date. Although a prototype of a submerged cutter head suction dredge was

Figure 5-il.–Conceptual Design for Suction Dredge Mounted on Semi-Submersible Platform



Semi-submersible platforms have been developed for offshore oil drilling. The semi-submersible platform offers a stable platform from which to operate, but is very expensive.

SOURCE: Dredge Technology Corp.

successfully built and operated offshore for several months, it was not an economic success and its development was discontinued.

Greater dredging depths can be attained by submerging pumping systems or by employing airlift or water jet lift systems. While submerged pump technology can be readily adapted from military submarine technology or from deep-water petroleum technology, the development costs are high.

No breakthroughs are foreseen that could vastly increase the capacities of offshore dredging systems and bring substantial cost reductions. However, existing technology is largely based on steel construction, and the use of new, lighter materials with higher strength-to-weight ratios has not been widely investigated.

MINING CONSOLIDATED MATERIALS OFFSHORE

Two principal types of consolidated deposits that are known to occur in the U.S. EEZ are massive polymetallic sulfides and cobalt-rich ferromanganese crusts. Alternatives for mining manganese nodules, where present in the EEZ, have much in common with dredging techniques used in shallow water, although the deep water in which nodules are found presents special problems. However, techniques for mining polymetallic sulfides and cobalt crusts are likely to be very different than the dredging techniques used to mine placers and other unconsolidated deposits. Unlike unconsolidated deposits, these deposits must be broken up (using either some type of mechanical device or blasting) and possibly must be crushed prior to transport to the surface. Moreover, all known cobalt crust and offshore polymetallic sulfide deposits occur in deep water, beyond the range of technologies used for conventional placer mining.

Much of the technology needed to mine massive polymetallic sulfide and cobalt crust deposits is yet to be developed. EEZ hard-rock deposits and massive polymetallic sulfide deposits are, therefore, probably of more scientific than commercial interest at this time. Research on the genesis, distribution, extent, composition, and other geological aspects of these deposits has been underway for only a few years, and more knowledge will likely be required before the private sector is likely to consider spending large sums of money to develop needed mining technology. A more immediate need is to refine the technology for sampling these hard-rock deposits (see ch. 4). Before mining equipment can be designed, more technical and engineering data on the deposits will be required.[2]

In the deep ocean, technology must be designed to cope with elevated hydrostatic pressure, the corrosive saltwater environment, the barrier imposed by the seawater column, and rugged terrain. Even onshore, mining equipment requires constant repair and maintenance. Given deep ocean conditions, it will be particularly important that mining equipment be as simple as possible, reliable, and sturdy.[3]

Massive Polymetallic Sulfides

Although technology for mining massive sulfides has not been developed, the steps likely to be required are straightforward. To start, any overburden covering the massive sulfides would have to be removed, although it is likely that initial mining targets would be selected without overburden. Then, the resource would then have to be fragmented, collected, possibly reduced in size, transported to a surface vessel, optionally beneficiated on the vessel, and finally transported to shore.

A number of conceptual approaches have been suggested to fragment and/or extract massive sulfides. These include use of cutter head dredges; drilling and blasting; high-pressure water jets; dozers, rippers, or scrapers; high-intensity shock waves; and in situ leaching.[4] All proposed extraction methods have some drawbacks, and none have been tested in the ocean environment. Crushing or grinding, where required, is not technically difficult on land but has not yet been done in commercial operations on the seafloor. Transport of crushed ore to the surface would most likely be accomplished by hydraulic pumping (using either airlift or submerged centrifugal pumps). This technology has been studied for mining seabed manganese nodule deposits, so it is perhaps the most advanced submerged part of many proposed hard-rock mining systems.

No major technical innovations are expected to be needed for surface ship operations, although the cost of equipment such as dynamically positioned semi-submersible platforms will be expensive. Onboard storage and transport of massive sulfide ore would have similar requirements as storage and transport of most other ores. Flotation technology for beneficiating massive sulfides has not yet been adapted for use at sea; however, the U.S. Bureau of Mines has initiated research on the subject.

One conceptual approach[5] for deposits on or just below the seafloor envisions the use of a bottom-mounted hydraulic dredge (figure 5-12). The dredge would be equipped with a suction cutter-ripper head capable of moving back and forth and also telescoping as it cuts into the sulfide deposit and simultaneously fractures and picks up the material by suction. The dredged material would be first pumped from the seabed to a crusher and screen system, then into a storage and injection hopper on the submerged dredge, and finally from the injection hopper to the surface. An airlift pump and segmented steel riser would give vertical lift. The surface platform would be a large, dynamically positioned, semi-submersible platform. After dewatering, the pumped material would be discharged into storage holds on the platform. In concept, the ore would be beneficiated on the platform, loaded on a barge,

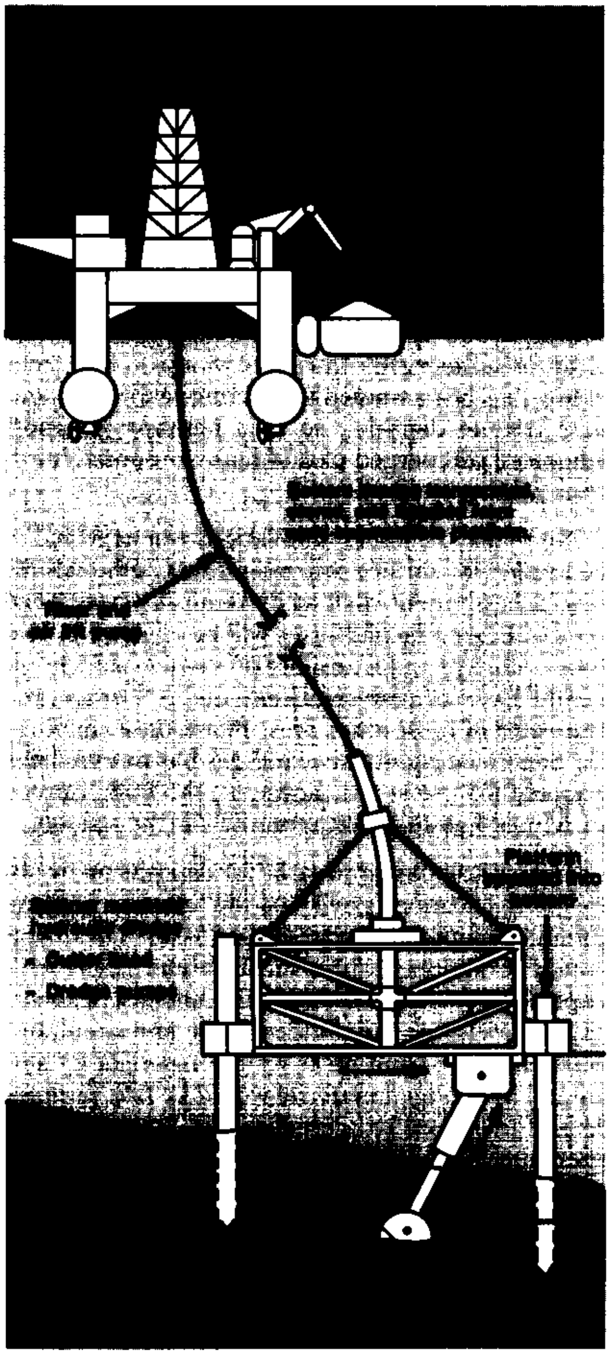
*R, Kaufman, ' 'Conceptual Approaches for Mining Marine Poly-metallic Sulfide Deposits, *Marine Technology Society Journal*, vol. 19, No. 4, 1985, p. 56.

[3]D. K, Denton, Jr, , ' 'Review of Existing, Developing, and Required Technology for Exploration, Delineation, and Mining of Seabed Massive Sulfide Deposits, U.S. Bureau of Mines, Minerals Availability Program, Technical Assistance Series, October 1985, p. 13,

'Ibid,, pp. 16-17

[5]Kaufman, ' 'Conceptual Approaches for Mining, " pp. 55-56.

Figure 5-12.—Conceptual System for Mining Polymetallic Sulfides



A prototype system for mining massive sulfides will unlikely be developed until the economics improve and more is known about the deposits (not to scale).

SOURCE: R. Kaufman, “Conceptual Approaches for Mining Marine Polymetallic Sulfide Deposits,” *Marine Technology Society Journal,* VOl 19, No. 4, 1985, p. 56.

and finally transported to shore using a tug-barge system. While such approaches seem reasonable given the current state of knowledge, a prototype mining system may be very different. It will not be possible to develop such a system until more is known about the nature of massive sulfides and until there is a perceived economic incentive to mine them.

Cobalt-Rich Ferromanganese Crusts

Cobalt-rich ferromanganese crusts on Pacific seamounts have been known for at least 20 years. However, knowledge that the crusts could some day be an economically exploitable resource is recent, and technology for mining the crusts is no more advanced than technology for mining massive sulfides.

Despite lack of technology and detailed information about the resource, a consortium (consisting of Brown & Root of the United States, Preussag AG of West Germany, and Nippon Kokan of Japan) has expressed interest in mining cobalt-rich crusts in the U.S. EEZ surrounding the State of Hawaii and Johnston Island. Most observers expect that crusts, if mined at all, are likely to be mined before sulfides. With this in mind, Hawaii and the U.S. Department of the Interior have recently prepared an Environmental Impact Statement (EIS) in which the resource potential and potential environmental impacts of crust mining in the Hawaiian and Johnston Island EEZs are assessed.

In addition, a relatively detailed mining development scenario has been prepared as part of the ***EIS.***[6] The scenario describes and evaluates the various subsystems required to mine crusts. A number of approaches are possible for each subsystem, but the basic tasks are the same. Subsystems would be required to fragment, collect, and crush crust and probably to partially separate crust from substrate before conveying ore to the surface. The surface support vessel and subsystem for pumping ore

[6]U. S. Department of the Interior, Minerals Management Service, and State of Hawaii, Department of Planning and Economic Development, *Proposed Marine Mineral Lease Sale in the Hawaiian Archipelago and Johnston Island Exclusive Economic Zones* (Draft Environmental Impact Statement), app. A: “Mining Development Scenario Summary, ” January 1987.

to the surface probably would be similar to those already designed for mining manganese nodules.

Crusts form thin coatings on the surface of various types of nonvaluable substrates. A principal problem in designing a crust mining system will be to separate crust from substrate in order to minimize dilution of the ore. The thickness and continuity of the crust (which are often highly variable), the nature of its bonding to substrate, and the efficiency of the cutting device used will affect how much substrate is collected. The more substrate collected, the lower the ore grade and the greater the costs of transportation, processing, and waste disposal. The principal alternatives are to separate crust from unwanted substrate on the seabed (and thus avoid lifting substrate to the surface) or to separate crust and substrate on the mining vessel. Complete separation on the seabed of ore from waste material would be preferable (if at all feasible), but costs to do so may be prohibitively high. It is more likely that only a small amount of the necessary separation will take place on the seabed and that most of the separation will take place on the mining vessel or onshore.

The mining system assumed in the EIS mining scenario employs a controllable, bottom-crawling tracked vehicle attached to a mining ship by a hydraulic lift system and electrical umbilical cord. However, before mining concepts can be significantly refined, more information will be required about the physical characteristics of the crusts. More data on the microtopography of crusts and substrate are an especially important requirement for the design of the key element of the mining system, a crust fragmenting device.

SOLUTION/BOREHOLE MINING

Solution or borehole mining has much in common with drilling for oil and gas; in fact, much of the technology for this mining method is borrowed from the oil and gas industry. Both terms refer to the mining of rock material from underground deposits by pumping water or a leaching solution down wells into contact with the deposit and removing the slurry or brine thus created. Because the mining process is accomplished through a drill hole, this method is applicable for recovering some types of ore without first removing overburden.

The Frasch process, used since 1960 to mine sulfur from salt dome deposits in the Gulf of Mexico, is the only current application of solution mining offshore (figure 5- 13). From an offshore drilling platform, superheated water and compressed air are pumped into the sulfur deposit. The hot water melts the sulfur, and liquid sulfur, water, and air are forced to the surface for collection. [7]

Borehole mining has been considered for recovery of both onshore and offshore phosphates. The U.S. Bureau of Mines has tested a prototype borehole mining tool onshore. For mining, the tool is lowered into a predrilled, steel-cased borehole to the ore. A rotating water jet on the tool disintegrates the phosphate matrix while a jet pump at the lower end of the tool pumps the resulting slurry to the surface. The slurry is then transported to a beneficiation plant by pipeline. The resulting cavity is backfilled with sand to prevent subsidence.

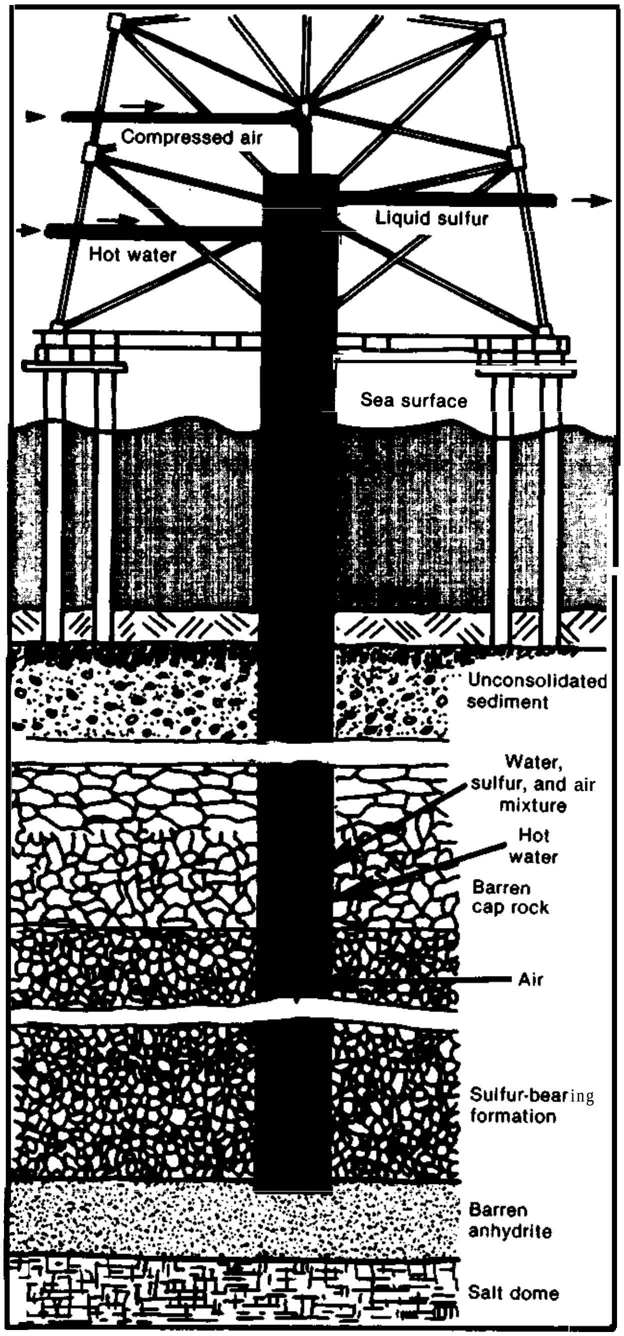
Results of economic feasibility studies of using the borehole mining technique onshore show that, where the thickness of the overburden is greater than 150 feet, borehole mining may be more economical than conventional surface mining systems.[8] An elaborate platform would be required for mining offshore deposits, so capital costs are expected to be higher than for onshore deposits. Borehole mining of phosphate appears to be less destructive to the environment than conventional phosphate mining techniques and, if used offshore, would probably not require backfilling of cavities.

Solution mining also has been mentioned as a possible technique for mining offshore massive sulfides. Significant drawbacks include the application of chemical reagents capable of leaching these sul-

[7] 1) E Morse, "Sulfur, " *Mineral Facts and Problems— 1985 Edition*, Bullet in 67.5 (Washington, DC L'. S Bureau of' Mines, 1 986), p 785.

[8] J. A. Hrabik and D J Godesky, " Economic Evaluat ion of Borehole and Con\' entional Mining Systems in Phosphate Deposits,'' *Bureau of' Mines Information Circular 8929*, 1983.

Figure 5-13.—Schematic of Solution Mining Technology (Frasch Process)



Solution mining of sulfur is currently done in the Gulf of Mexico. Borehole mining, which has been suggested for mining phosphorite, is similar, using high pressure water to disintegrate ore below overburden. The resulting slurry is then pumped to the surface.

SOURCES: *Encyclopedia Americana, vol. 25* (Danbury, CT: Grolier, Inc., 1986), p. 868; J.W. Shelton, "'Sulfur," *Mineral Facts and Problems, 1980 ed.* (Washington, DC: U.S. Bureau of Mines), p. 864.

fides, possible contamination of seawater by the chemical leach solutions required, and the probable necessity of fracturing impermeable deposits to allow the leach solution to percolate through the deposit. Solution/borehole technology is untested on marine hard-rock deposits.[9]

[9]Denton, "Review of Existing, Developing, and Required Technology.

OFFSHORE MINING TECHNOLOGIES

Unless concentrations of mineral deposits offshore are likely to be much higher than those on land, or unless the values of minerals increase, it is apparent that the mining industry will have less incentive to develop new technology than an industry like the petroleum industry. For example, the value of oil from a relatively small offshore field is likely to approach $1 billion. In comparison, a reasonable target for an offshore placer gold deposit might have a value of $100 million—an order of magnitude less.

Massive sulfides and other primary mineral deposits of the EEZ may some day present economic targets and offer incentives to development of mining technologies. These technologies are likely to depart significantly from dredging concepts and may be more closely related to solution mining, offshore petroleum recovery, or conventional techniques of hard rock mining.

Many of the technological advances made by the offshore petroleum industry would find applications in offshore mining, provided the offshore mineral deposits were rich enough to sustain the capital and operating costs of such developments. This technology transfer was demonstrated during the 1970s when several groups of leading international companies in the mining industry sponsored development work on methods for mining manganese nodules from depths of about 15,000 feet. These groups have delayed their plans for dredging nodules, primarily because prices for copper, nickel, cobalt, and manganese continue to be low, but also because the institutional regime imposed on the exploitation of the international oceanfloor is still evolving,

AT-SEA PROCESSING

Mineral processing involves separating raw material (ore) from worthless constituents and transforming it into intermediate or final mineral products. The number and type of steps involved in a particular process may vary considerably depending on the characteristics of the ore and the end product or products to be extracted. Mineral processing encompasses a wide range of techniques from relatively straightforward mechanical operations (beneficiation) to complex chemical procedures. Processing may be needed for one or more of the following tasks:

1. To ***control particle size:*** This step may be undertaken either to make the material more convenient to handle for subsequent processing or, as in the case of sized aggregate, to make a final product suitable for sale.
2. ***To expose or*** *release constituents for further processing:* Exposure and liberation are achieved by size reduction. For cases in which minerals must be separated by physical processes, an adequate amount of freeing of the different minerals from each other is a prerequisite.
3. ***To*** *control* ***composition:*** Constituents that would make ore difficult to process chemically or would result in an inadequate final product must be eliminated or partially eliminated (e. g., chromite must be removed from ilmenite ore in order to meet specifications for pigment). Often, an important need is to eliminate the bulk of the waste minerals from an ore to produce a concentrate (beneficiation).[10]

Processing of marine minerals may take place either on land or at sea or partly on both land and sea, depending on economic and technological considerations. Where processing is to be done wholly or partly at sea, it is integrated closely with the mining operation. However, since almost no mining has taken place to date in the EEZ, offshore processing experience is limited. Processing technology for minerals found on land has developed over many centuries and, in contrast to requirements for offshore processing, has been designed to operate on stable, motionless foundations and, with few exceptions, to use fresh water.

It is usually not desirable to do all processing of marine minerals offshore. Final recovery may be done onboard in the case of precious minerals, such

[10]E.G. Kelly and D.J. Spottiswood, *Introduction to Mineral Processing* (New York, NY: John Wiley & Sons, 1982), pp. 5-6.

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as gold, platinum, and diamonds, but all other minerals would probably be taken ashore as bulk concentrates to be further processed. Trade-offs must be considered in evaluating whether to partially process some minerals offshore. First, the cost of transporting unbeneficiated ore to shore must be weighed against the added costs and capital expenses of putting a beneficiation plant offshore. Transportation to shore of a smaller amount of high grade concentrate may be more economical than transporting a larger amount of lower grade ore to shore for beneficiation and subsequent processing. (This is also a standard problem on land when evaluating trade-offs between, for example, building a smelter or investing in transportation to an existing smelter.) Second, it is generally thought to be easier and more economical to discharge tailings (waste materials) at sea than on land, but tailings discharge may result in unacceptable environmental impacts. Third, while seawater is an unlimited source of water for use in many phases of processing, its higher salinity could make processing more difficult and concentrates could require additional washing with fresh water.

Important considerations in evaluating whether to process minerals offshore may include the cost of space aboard mining vessels and the sensitivity of some processing steps to vessel motion. Space is an important factor in the economics of a project. Since larger platforms cost more, engineers must consider the trade-offs between using a hull or platform large and stable enough to contain additional processing equipment, power, fuel, storage space, and personnel and transporting unbeneficiated ore to shore. Although little experience is available, vessel motion may make some processing steps difficult or impossible without motion compensation equipment and may significantly reduce the efficiency of recovering some minerals. Power requirements are also of major concern because all power must be generated onboard, thus requiring both additional space and costs. Personnel safety, the availability of docking facilities, distance to refineries, and production rates may also influence processing decisions.[11]

[11] M.J. Cruickshank, ''Marine Sand and Gravel Mining and Processing Technologies, *Marine Mining,* in press.

Some basic development options include limiting the motion of the platform (e. g., by using a semi-submersible); isolating the processing equipment from platform motion (e. g., by mounting it on gimbals); redesigning the processing equipment to make it more efficient at sea; or simply accepting lower grade concentrate by using existing and, hence, less costly equipment. In the case of mineral processing, an initial priority probably would be to test existing processing equipment at sea to obtain operating experience.

The costs and efficiency of operating a processing plant at sea are highly uncertain. For example, motion compensation of specific sections of the onboard plant or of major portions of the vessel is expensive. For most minerals, further development of technology will be needed to optimize offshore mineral processing equipment and procedures. In general, one would probably attempt to perform the easy and relatively inexpensive processing steps offshore, such as size separation and rough gravity concentration, to reduce the bulk of material to be transported, then complete the processing on land.

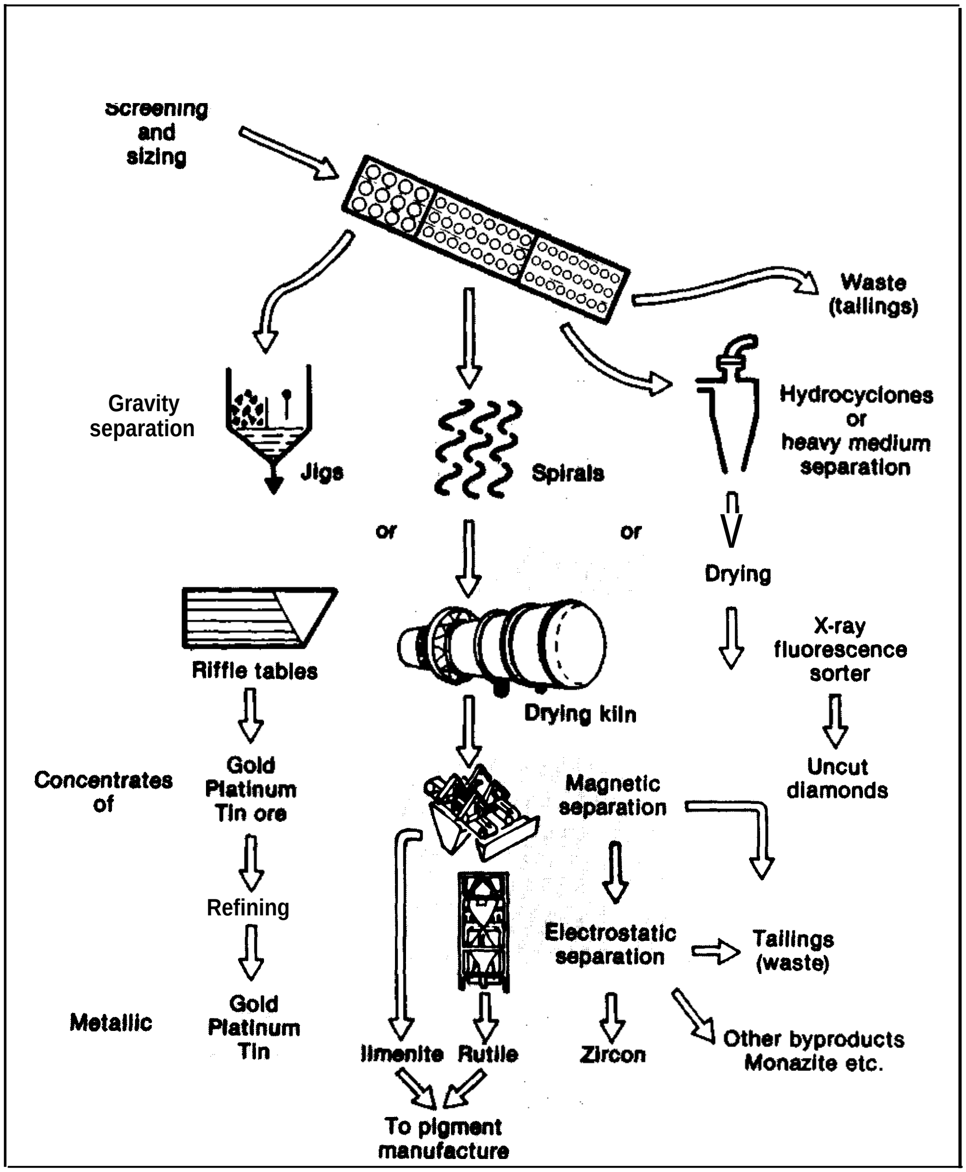
There are three broad categories of mineral processing technology:

1. technology for unconsolidated deposits of chemically inert minerals,
2. technology for unconsolidated or semi-consolidated deposits of chemically active minerals, and
3. technology for consolidated deposits of minerals requiring crushing and size reduction.

Processing Unconsolidated Deposits of Chemically Inert Minerals

Chemically inert minerals include gold; platinum; tin oxide (cassiterite); titanium oxides (ilmenite, rutile, and leucoxene); zircon; monazite; diamonds; and a few others. These occur in nature as mineral grains in placers (see ch. 2) and are often found mixed with clay, sand, and/or gravel particles of various sizes. Since these minerals are generally heavier than the silicate and other minerals with which they may be mixed, the use of mechanical gravity separation methods is important in processing (figure 5-14), However, the initial step

Figure 5-14.—Technologies for Processing Placer Mineral Ores



Offshore screening, sizing, and gravity separation may be adopted to reduce the amount of material that must be brought to shore. Drying and magnetic and electrostatic separation steps will most likely take place ashore.

SOURCE Off Ice of Technology Assessment, 1987.

in processing ores containing mineral grains of various sizes is usually size separation.

Size separation may be needed to control the size of material fed to other equipment in the processing stream, to reduce the volume of ore to be concentrated to a minimum without losing the target mineral(s), and/or to produce a product of equal size particles. Separation is accomplished by use of various types of screens and classifiers. Screens —uniformly perforated (and sometimes vibrating) surfaces that allow only particles smaller than the aperture size to pass—are used for coarser materials.[12] The size of screen holes varies with the ma-

''Ibid

terial, production capacity of the dredge, and other factors. For example, sand and gravel alone may constitute the valuable mineral fraction. To be sold as commercial aggregate, sand and gravel are generally screened to remove the undesirable very fine and very coarse fractions.

One type of size separation device in common use on dredges is the trommel. A trommel is simply a rotating cylindrical screen, large enough and strong enough to withstand the shock and abrasion of thousands of tons of sand and gravel sliding and tumbling through it each hour. If the material is mined by a bucket dredge, the material may be disaggregate by powerful water jets while it slides downward through a rotating trommel. If the material is mined by a suction dredge, it may already be disaggregated but may need dewatering before screening. In either case gravity plays an important role, since the material must first be elevated in order to slide downward through the screens.

Classifiers are used for separating particles smaller than screens can handle. Classifiers separate particles according to their settling rate in a fluid. One type in common use is the hydrocyclone. In this type of classifier, a mixture of ore and water is pumped under pressure into an enclosed circular chamber, generating a centrifugal force. Separation takes place as the heavier materials fall and are discharged from the bottom while the lighter particles flow out the top. Hydrocyclones are mechanically simple, require little space, and are inexpensive. Most offshore tin, diamond, and gold mining operations separate material by screening and/or cycloning as a first step in mineral recovery.

Following size separation, gravity separation techniques are used to concentrate most of the minerals in this category. By gravity, the valuable heavier minerals are separated from the lighter, less valuable or worthless constituents of the ore. Processing by gravity concentration takes advantage of the differences in density among materials. Several different technologies have been developed, including jigs, spirals, sluices, cones, and shaking tables. 13

Jigging is the action of sorting heavier particles in a pulsating water column. Using either air pressure or a piston, the pulsations are imparted to an introduced ore-water slurry. This action causes the heavier minerals to sink to the bottom, where they are drawn off. Lighter particles are entrained in the cross-flow and discharged as waste. Secondary or tertiary jigs may be used for further concentration. Several different types of jig have been developed, including the circular jig, which has been used extensively on offshore tin dredges in Southeast Asia. Jigs also have been used successfully offshore to process alluvial gold and diamonds. For example, they have proved effective in eliminating 85 to 90 percent of the waste material from tin ore (cassiterite) in Indonesia and from gold ore in tests near Nome, Alaska.

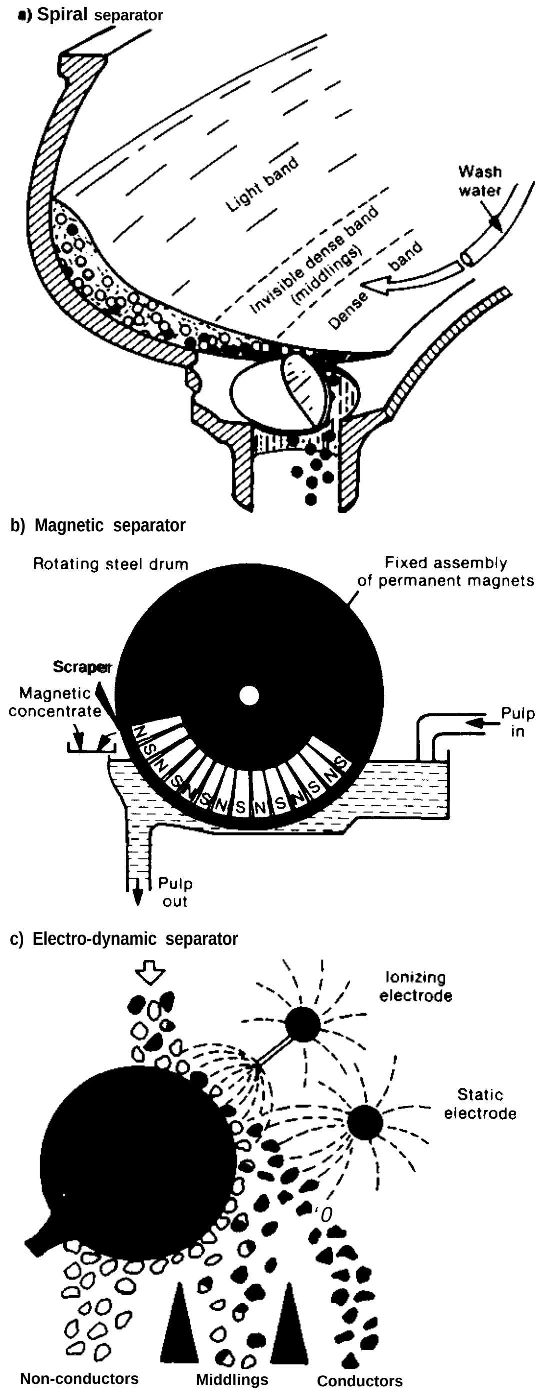
Some jigs may be sensitive to the rolling and pitching motion of a mining dredge at sea, depending in part on the severity of the motion and in part on their location aboard the dredge (usually high above the deck to use gravity to advantage), This has not been a major problem on Indonesian offshore bucket dredges, although sea conditions there are not as rough as in other parts of the world. Design of dredges for less rolling motion and for reduced sensitivity to wind forces (e. g., by placing the processing plant and machinery below the waterline) would alleviate this problem, Lower profile dredges could be designed without much difficulty, provided economic incentives existed to do so.

A simple gravity device for concentrating some placer minerals onshore is a riffle box for sluicing material. Although neither well understood nor very efficient, sluicing is the one of the oldest types of processing technology for concentrating alluvial gold or tin. In addition to their simplicity, sluices are rugged, passive, and inexpensive, Although sluices have not been used offshore, they might be utilized to beneficiate ore of low-value heavy minerals such as ilmenite or chromite.

Many other types of gravity separation devices are used onshore to separate inert heavy minerals from mixtures of ore and water. The most common are spirals (e. g., Humphrey's spirals) and cyclones. Spirals (figure 5-1 5) are used extensively to concentrate ilmenite, rutile, zircon, monazite, chromite, and magnetite from silicate sands of dunes and ancient shorelines. The effectiveness of spirals mounted on platforms subject to wave motions is not well known, but spirals have been used

[13] Ibid

Figure 5-15.—Operating Principles of Three Placer Mineral Separation Techniques



Gravity separation using spirals may be adapted for offshore use in some circumstances. Magnetic and electro-dynamic separation will most likely be done on land.

SOURCE: E G KeHey and D J Spottiswood, *Introduction to Mineral Processing (New* York John Wiley & Sons, 1982).

successfully for sample concentration on board ship. In operation, an ore-water slurry is introduced at the top of the spiral. As the slurry spirals downward, the lighter minerals are thrown to the outside by centrifugal force, while the heavy minerals concentrate along the inner part of the spiral. The heavy minerals are split from the slurry stream and saved. Spirals have lower rates of throughput than jigs. Moreover, more space would be required to process an equal volume of minerals, and spirals are unsuited for separating particles larger than about one-quarter inch,

Another form of heavy mineral processing that may have applications offshore is heavy media separation. This gravity separation technique uses a dense material in liquid suspension (the heavy medium) to separate heavy minerals from lighter materials. The "heavies' sink to the bottom of the heavy medium, while lighter materials, such as silicates, float away. The heavy liquid is then recirculated. This technique has been used effectively offshore to recover diamonds. However, it is expensive and its use may contaminate seawater.

Initial "wet" concentration at sea results in a primary concentrate. Much of the technology for size classification and gravity separation of minerals appears to be adaptable for use at sea for making primary concentrates without major technological problems. For further preparation for sale, concentrates of heavy minerals are usually dried and separated on shore. For example, ilmenite and magnetite are considered impurities in tin ore and must be eliminated. Producing heavy mineral concentrates for final sale may also involve further gravity separation, drying in kilns, and/or elaborate magnetic and electrostatic separation operations.

Magnetic separation is possible for those minerals with magnetic properties (figure 15-5). For example, magnetite may be separated from other heavy minerals using a low-intensity magnetic separation technique. Ilmenite or other less strongly magnetic minerals may be separated from nonmagnetic minerals using a high-intensity technique. Separation at sea of strongly magnetic minerals is possible, but separation of minerals with small differences in magnetic susceptibility may have to be done on land. Magnetite has the highest magnetic susceptibility. In decreasing order of susceptibility are ilmenite and chromite; epidote and xenotime; apatite, monazite, and hematite; and staurolite.

Conducting minerals may be separated from nonconductors using electrostatic separation. Only a few minerals are concentrated using this method, but electrostatic separation is used very successfully to separate heavy mineral beach sands, such as rutile and ilmenite from zircon and monazite. [14] Figure 5-15 illustrates how conducting and nonconducting minerals and "middlings" are split from each other using an electro-dynamic separator. During processing, the feed particles acquire an electrical charge from an ionizing electrode. Conducting minerals lose their charge to the grounded rotor and are thrown from the rotor's surface. A non-ionizing electrode is then used to attract conducting minerals further away from the rotor. Nonconductors do not lose their charge as rapidly and so adhere to the grounded rotor until they do lose their charge or are brushed off. Middlings may be run through the electrostatic separator again. 15 Electrostatic separation is usually combined with gravity and magnetic separation methods when separating minerals from each other.

Many of these technologies require adjustments, depending in part on the volume and grade of ore passing through the plant and on the ratio of input ore to output concentrate or final product. The ratios of valuable mineral to ore mined are shown in table 5-3 for some typical heavy minerals. The amount of primary concentrate produced by jigs on a dredge mining 30,000 cubic yards of gold ore per day would be on the order of a few tons (depending on the other heavy minerals present); initial processing of 30,000 cubic yards per day of ilmenite ore would yield a few hundred tons of primary concentrate.

The amount of machinery, space, and power needed for producing a final concentrate or product varies widely for different minerals. Final separation and recovery of ilmenite, rutile, zircon, and monazite require elaborate plants that occupy large spaces and consume large amounts of energy. These heavy minerals are first dried in long kilns, then passed through batteries of magnetic and electrostatic separators. Experience using these technologies is mostly on land, and there do not appear to be any economic advantages to undertaking final separation and recovery of these minerals offshore. Conversely, technologies for final recovery of diamonds, gold, and tin occupy little space and consume little power. Some techniques (e. g., shaking tables) require flat, level platforms. Final recovery of gold by amalgamation with mercury can be easily done at sea if the mercury is safely contained. Final separation of diamonds from concentrates is done using X-rays.

[14] Ibid.
[15] Ibid.

Table 5-3.—Ratio of Valuable Mineral to Ore

	In ore mined	In primary concentrate
Diamonds	1:5,000,000	1:1 ,000
Gold, platinum . . .	1:2,000,000	1:1,000
Tin	1:1 ,000	1:100
Ilmenite, etc.	1:100	1:10

SOURCE Office of Technology Assessment, 1987.

Processing Unconsolidated or Semi-Consolidated Deposits of Chemically Active Minerals

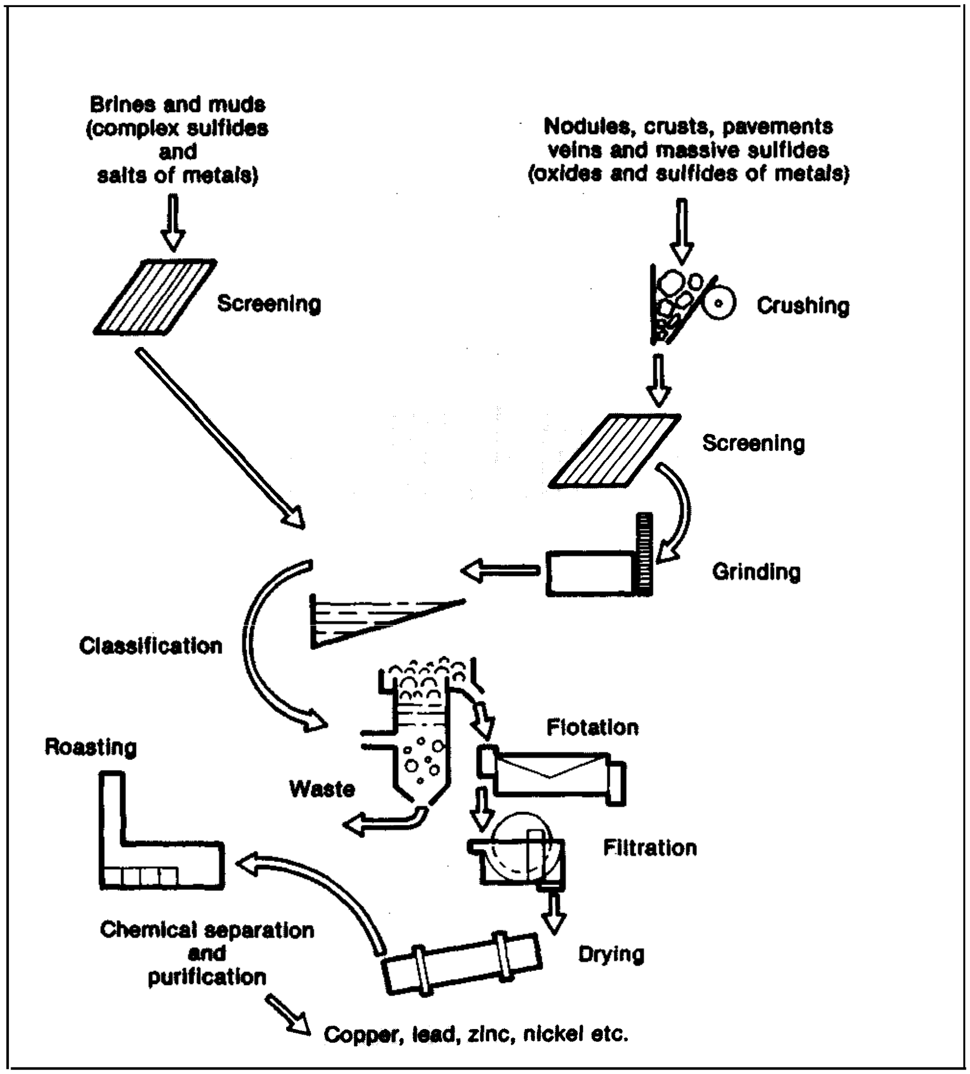
Examples of unconsolidated or semi-consolidated deposits of chemically active minerals include minerals found in such deposits as the Red Sea brines and sulfide-bearing sediments on the Outer Continental Shelf. In general, the minerals of economic interest in ore deposits of this type are complex sulfides of base metals such as copper and zinc, and minor quantities of precious metals (mainly silver).

This type of mineral is generally concentrated on land using flotation technology (figure 5-16). Flotation concentration is based on the surface chemistry of mineral particles in solution. Methods vary, but all employ chemical reagents that interact with finely crushed sulfide particles to make them selectively hydrophobic. The solution is aerated, and the hydrophobic minerals adhere to the air bubbles and float to the surface (other mineral particles sink to the bottom), A froth containing the floated minerals is formed at the surface of the solution and is drawn off.[16] Flotation concentrates are collected on filters and dried prior to further pyrometallurgical processing (e. g., smelting) to separate individual metals.

Experimental flotation of metalliferous muds at a pilot-scale plant in the Red Sea is the only experience using this process offshore. Since wind,

[16] Ibid.

Figure 5-16.—Technologies for Processing Offshore Mineral Ores



Consolidated deposits of nodules, crusts, and massive sulfides require crushing and grinding in addition to the screening required for brines and muds. Flotation is the primary technique for separating oxides and sulfides of metals from waste material. These processes have not yet been adapted for use offshore.

SOURCE: Office of Technology Assessment, 1987

wave, and current conditions in the Red Sea are not as severe as in the open ocean, these tests are not conclusive regarding the sensitivity of flotation methods to ship motion. Disposal of flotation reagents at sea may be a problem in some cases and should be further investigated.

Processing Consolidated and Complex Mineral Ores

Mineral deposits in this category include nodules, crusts, veins, pavements, and massive deposits, as of metalliferous sulfides or oxides. Processing of these minerals is likely to require crushing or grinding to reduce particle size, followed by chemical separation methods. In some cases (i. e., for gold veins) fine grinding may liberate minerals which then may be recovered using gravity separation alone. However, in most cases some flotation and/or other chemical processing is likely to be required. The Bureau of Mines has experimented with column flotation techniques for separation of cobalt-rich manganese crust from substrate. Crust separated in this manner, however, cannot simply be concentrated by inexpensive mineral processing techniques. Most of these processes have not been adapted for use at sea. Crushing and grinding circuits could be mounted on floating platforms or on the seafloor, but unless the economic incentive to mine this type of seafloor deposit improves, these techniques will not likely be used offshore in the near future. The same comment applies to flotation and other chemical processing technologies.

OFFSHORE MINING SCENARIOS

To illustrate the feasibility of offshore mining, OTA constructed five scenarios, each depicting a prospective mining operation in an area where elevated concentrations of potentially valuable minerals are known to occur. The scenarios illustrate factors affecting the feasibility of offshore mining, including the physical and environmental conditions that may be encountered offshore, the capabilities of the available mining and processing technologies, and estimated costs to mine and process offshore minerals. The scenarios selected include mining of:

- titanium-rich sands off the Georgia coast,
- chromite sands off the Oregon coast,
- gold off the Alaska coast near Nome,
- phosphorite off the Georgia coast near Tybee Island, and
- phosphorite in Onslow Bay off the North Carolina coast.

These shallow-water mineral deposits were selected because they are judged to be potentially mineable in the near term, unlike, for example, deposits of cobalt-rich ferromanganese crusts or massive sulfides, both of which would require considerable engineering research and development.

For each scenario, the ocean environments are considered to be acceptable for dredging operations, dredging technologies are judged to be available with little modification, and existing processing technologies are considered adaptable for shipboard use, although some development will be needed. The greatest uncertainties arise from lack of data on the nature of the placer deposits (except for Nome, reserves have not been proven by drilling) and from the lack of operating experience under conditions encountered in the U.S. EEZ (i. e., waves and long-period swells).

OTA did not attempt detailed engineering and cost analyses. Too little information is currently available to accurately assess the profitability of offshore mining. For example, the grade of ore may vary considerably throughout a deposit, but little information about grade variability has been compiled yet at any site. Estimates of mining and processing costs can vary considerably depending on the amount of information on which they are based. Given that estimates cannot now be based on detailed information, OTA has attempted simply to estimate the range within which costs are most likely to fall. Rough estimates do not satisfy the need for detailed feasibility studies based on comprehensive data; however, they do provide criteria with which to judge if recovery of large quantities of high grade, valuable minerals on the seabed is likely to be profitable or at least competitive with land-based sources of minerals.

Similar scenarios for titanium, chromite, and gold placers also have been developed recently by the U.S. Bureau of Mines.[17] The scenarios are not directly comparable, but, after allowing for different assumptions and uncertainty, the general conclusions reached are roughly the same. Tables 5-9, 5-10, and 5-11 at the end of the chapter compare OTA and Bureau of Mines scenarios.

[17] *An Economic Reconnaissance of Selected Heavy Mineral Placer Deposits in the U.S. Exclusive Economic Zone*, Open File Report 4-87 (Washington, D. C.: U.S. Bureau 01 Mines, January 1987).

Offshore Titaniferous Sands Mining Scenario

Location.—Concentrations of titaniferous sands are known to occur on the seabed adjacent to the coast of Georgia (figure 5-17). These sands constitute a resource of titanium oxide minerals (primarily ilmenite, but also lesser amounts of rutile and leucoxene, (figure 5-18)) and associated light heavy minerals. However, little detailed exploration has been done in the area, so the extent and grade of the resource is not precisely known.

Two mineral companies that mine onshore titaniferous sands in nearby northeastern Florida have expressed interest in the area. In fact, in 1986, the Minerals Management Service issued geological and geophysical exploration permits to Associated Minerals U. S. A., Ltd., and E.I. du Pont de Nemours & Co. The companies have undertaken shallow coring, sub-bottom profiling, and radiometric surveys in the area. The area of interest extends from Tybee Island in the north to Jekyll Island in the south, a distance of about 85 nautical miles, and from State waters to about 30 nautical miles offshore. The proximity of onshore titanium mineral processing facilities in northeastern Florida is a particular reason this scenario site was selected over other potential sites on the Atlantic Ocean continental shelf.

Operational and Geological Characteristics.—Within this area, a typical mine site was selected approximately 30 nautical miles offshore. Water depths at this site average 100 feet. Northeasterly winds tend to prevail from October to March. The site is in the path of occasional "northeasters' and hurricanes, but wind, wave, tide, and current conditions are otherwise moderate. Wave heights of 6 feet are common during winter months, but waves of 1 to 4 feet are more typical the rest of the year. Infrequent severe storms may produce waves in excess of 20 feet, typically from the southeast or northeast. It is assumed that operations can be conducted 300 days per year.

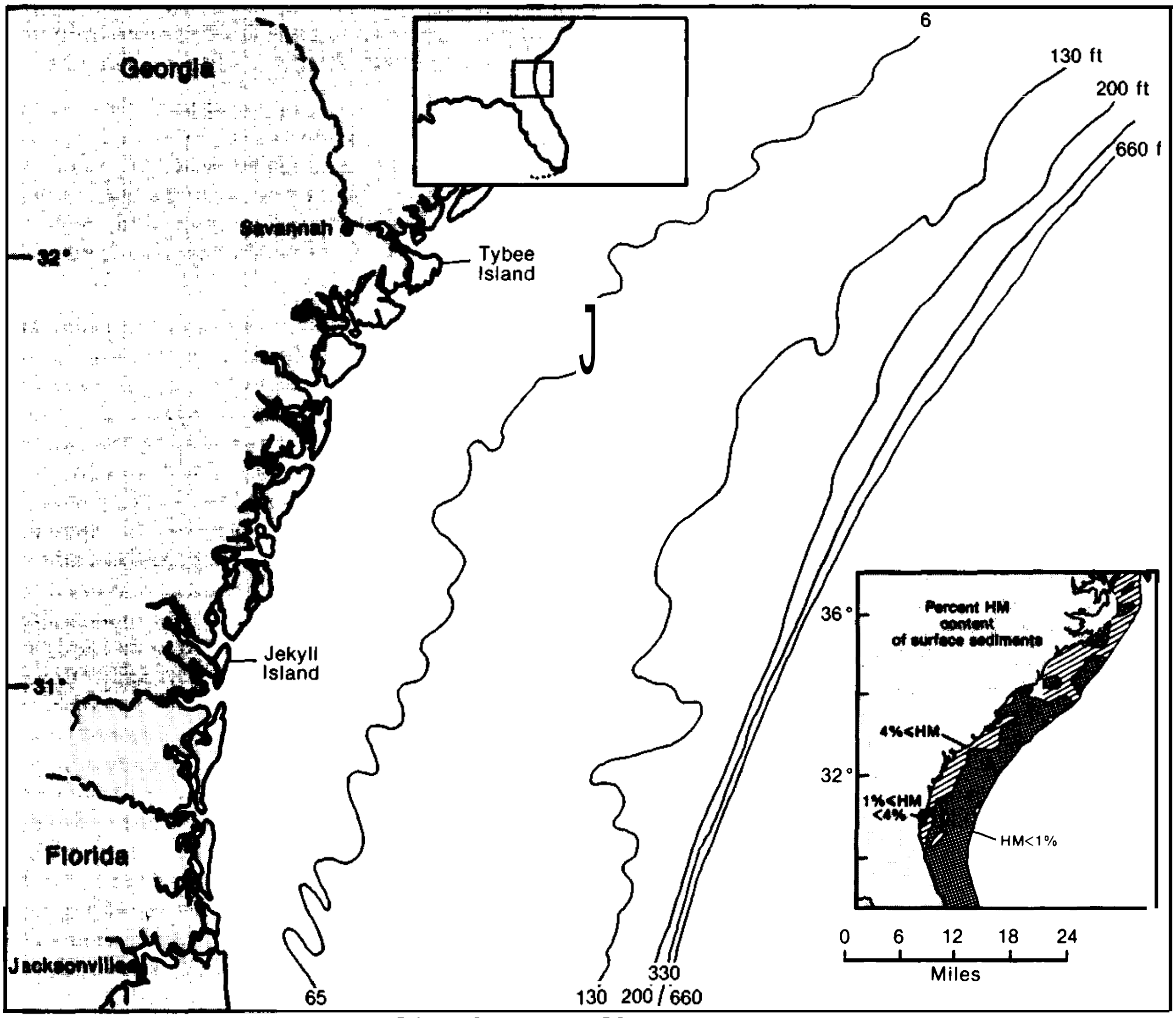
The geological features of the site were identified primarily by sub-bottom profiling and include buried stream channels and submerged shorelines. A similar ancient shoreline target onshore in northeastern Florida would be 12 miles long, 1 mile wide, and 20 feet thick. Little is known about any overburden at this time, so it is assumed that the deposit, like similar deposits onshore at Trail Ridge, Florida, consists of unconsolidated heavy mineral sands without significant overlying sediments.

The average concentration of total heavy minerals in the ore is assumed to be between 5 and 15 percent by weight, about half of which are economic heavy minerals. This range includes the average grade of the heavy mineral concentrations detected in the few samples from the site that have been analyzed to date.

Mining Technology.—The most appropriate technology for mining titaniferous minerals at the selected site is considered to be a trailing suction hopper dredge. This dredge is capable of operating in the open ocean at the mining site and of shuttling to and from its shore base during the normal seas expected in this region. Trailing suction hopper dredges have been widely used for sand and gravel mining and for removing unconsolidated material from harbors and channels. It is assumed that the titaniferous sand is at most only mildly compacted. The unconsolidated mineral sands are sucked up the drag arms, which can adjust to vessel heave and pitch to maintain the suction head on the seabed. A booster pump is installed in the suction line, enabling the dredge to reach minerals at the assumed bottom of the mineralized zone, about 120 feet below sea level. If cutting force is needed to loosen the compacted sand and clay, high-pressure water jets and cutting teeth can be added to the suction head. A dredge with a hopper capacity of 5,000 cubic yards is used. The dredge is assumed to be of U.S. registry, built and operated according to Coast Guard regulations, and more expensive than a similar dredge built abroad. All equipment is assumed to be purchased new at 1987 market prices.

At-Sea Processing.—The dredge is outfitted with a wet primary concentration plant capable of producing 450,000 tons per year of heavy mineral concentrate for delivery to a dry mill on shore. The efficiency of economic heavy mineral recovery is assumed to be 70 percent for the wet plant and 87.5 percent for the dry plant. The final product concentrate supplies the raw material for a pigment plant. It is assumed that no major technical problems are encountered in designing the primary con-

Figure 5-17.—Offshore Titaniferous Mineral Province, Southeast United States



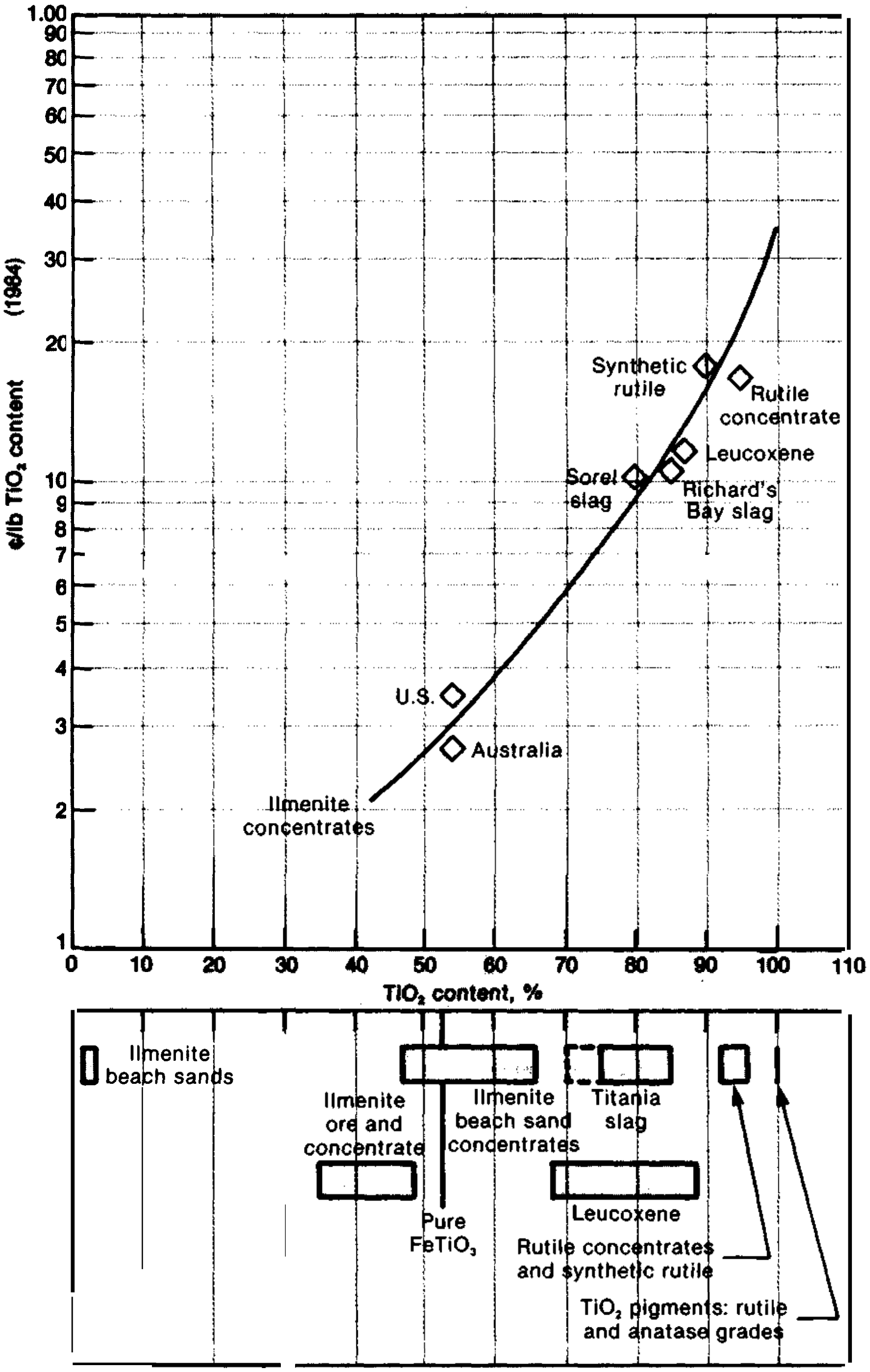
URCES: Office of Technology Assessment, 1987; A.E. Grosz, J.C. Hathaway, and E.C. Escowitz, "Placer Deposits of Heavy Minerals in Atlantic Continental Shelf Sediments," Proceedings of the 18th Annual Offshore Technology Conference, Houston, TX, May 5-8, 1986.

centration plant to compensate for operation on a moving vessel, and that the processing subsystems do not require significant and/or expensive development work. The onboard processing plant produces the primary concentrate using conventional particle size separation and gravity separation equipment. Seawater is used in the gravity separation process. Production of 450,000 short tons per year of primary concentrate implies mining rates between 3.2 million and 9.5 million short tons of ore per year, corresponding to ore grades of 15 and 5 percent. Larger pumps consuming more power would be required to mine 5 percent ore at the same rate as 15 percent ore.

Mining and At-Sea Processing Cycle.—The mining and at-sea processing cycle consists of five steps:

1. The dredge steams to the mining site,
2. it dredges material from the seabed,
3. it preconcentrates the ore and fills up the hopper,

Figure 5-18.—Values of TiO_2 Content of Common Titanium Mineral Concentrates and Intermediates



SOURCE: W.W. Harvey and F.C. Brown, "Offshore Titanium Heavy Mineral Placers: Processing and Related Considerations," contractor report prepared for the Office of Technology Assessment, November 1986.

4. steams to the shore base, and
5. it discharges the preconcentrate from the hopper.

Each of these cycles takes 4 days: 3 days for dredging and processing and 1 day for transit and offloading. Seventy-five such cycles per year can be made using a trailing suction hopper dredge with a 5,000 - cubic-yard hopper capacity. This allows 60 days per year for drydocking, maintenance, and downtime due to weather or other contingencies. The average distance from offshore deposits to the shoreside discharge point is estimated to be 100 miles.

The requirement to stop dredging and return to port could be eliminated by loading shuttle barges instead of filling the dredge hoppers. Other alternatives to the scenario probably would be evaluated by prospective miners who, for example, might process to a higher concentrate grade offshore.

Capital and Operating Costs.—Total capital requirements are estimated to range from $55 million to $86 million, depending on average ore grade (ranging from 15 to 5 percent respectively). Capital costs include costs of the dredge, onboard wet mill, onshore unloading installation, dry mill, and working capital (table 5-4). Capital costs for both the dredge and onboard wet mill decrease as the ore grade increases because less mining (pumping) capacity is required. Total operating costs are higher for lower grade ore because more ore must be mined by a larger dredge to produce the same amount of concentrate. Annual costs to operate the dredge, wet mill, and dry mill, and for general and administrative expenses and depreciation are estimated to be from $25 million to $37 million, depending on the heavy mineral content(15 to 5 percent). Given these estimates for capital and operating costs, breakeven revenue requirements have been calculated to range from $170 to $250 per ton of marketable product.

Table 5-4.—Offshore Titaniferous Sands Mining Scenario: Capital and Operating Cost Estimates

	Ore grade		
	50/0	10 "/0	15%0
Capital costs (million $):			
Dredge	$40	$36	$32
Offshore processing	34	18	14
Onshore processing	4	4	4
Working capital	8	6	5
Total capital costs	$86	$64	$55
Annual operating costs (million $):			
Dredge and offshore processing	$17	$14	$12
Onshore processing	2	2	2
General and administrative	2	1	1
Depreciation expense	16	11	10
Total operating costs	$37	$28	$25

SOURCE: Office of Technology Assessment, 1987.

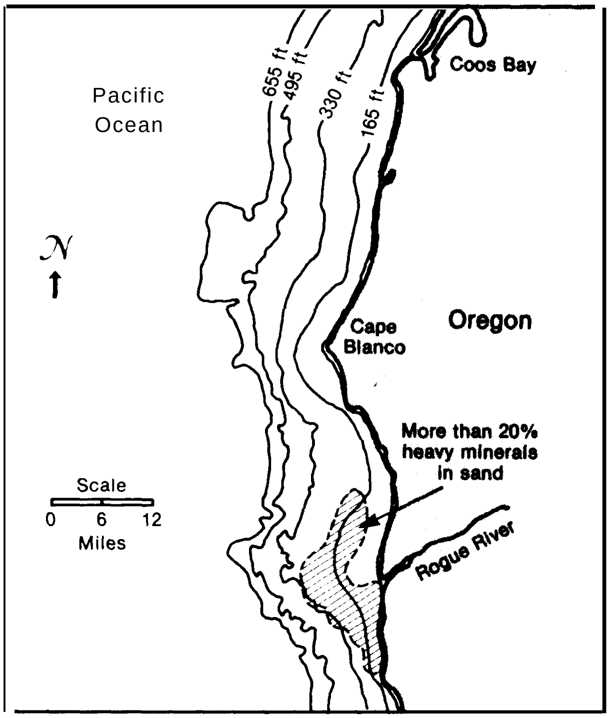
Given the risks inherent in developing an offshore deposit, the developers would expect higher returns than for a conventional land-based mineral sands operation and require a more rapid payback on investment. For example, under the 1986 tax law, a 3-year payback would require revenues of between $420 and $280 per ton of product for ore grades ranging from 5 to 15 percent. Since the current U.S. east coast price of ilmenite concentrate is $45 to $50 per short ton, it is clear that the deposit would require appreciable concentrations of other valuable minerals (e, g., rutile, zircon, and/or monazite with values ranging from $180 to $500 per ton) to be profitable.

Offshore Chromite Sands Mining Scenario

Location. —Concentrations of heavy mineral sands containing primarily chromite, lesser amounts of ilmenite, rutile, and zircon, and traces of gold and other minerals occur in surface and near-surface deposits on the continental shelf off southern Oregon (figure 5-19). Many reconnaissance surveys conducted by academic researchers have been completed in the area, but no detailed mineral exploration has taken place. The largest heavy mineral sand area appears to extend westward from the mouth of the Rogue River and northward toward Cape Blanco. A second area of chromite-rich black sands is located seaward of the mouth of the Sixes River. Additional small deposits occur on the continental shelf and on uplifted marine terraces between Coos Bay and Bandon. The Rogue River deposits are approximately 75 miles south of Coos Bay, the nearest deep-water industrial port, and 100 miles north of the port of Eureka, California.

No State or Federal exploration permits have been issued in the area to the private sector. However, one company, Oregon Coastal Services, has expressed interest in obtaining a permit to explore for minerals in State waters.

Figure 5-19.—Offshore Chromite Sands, Oregon Continental Shelf



SOURCE: Adapted from T Parmenter and R Bailey, *The Oregon Ocean Book* (Salem, OR: Oregon Department of Land Conservation and Development, 1985), p. 21

Operational and Geological Characteristics.—The site selected for this scenario lies seaward of the Rogue River, from 2 to 4 miles offshore. Water depths in the vicinity of the mine site are between 150 and 300 feet. The main deposit is assumed to be roughly 22 miles long by 6 miles wide and straddles the boundary between State and Federal waters.

Summer waves, generally from the northwest, are driven by strong onshore winds and range in height from 2 to 10 feet. In winter, waves are characteristically from the west or southwest and average 3 to 20 feet. The most severe storms, which occur from November through March, may occasionally produce wave heights in excess of 60 feet. The severity of the wave regime off the coast of Oregon has been compared to that of the North Sea. In addition to weather, a seasonal factor that may affect mining activity is prior use of the area by sea lions as a breeding ground and by salmon fishermen for sport and commercial fishing.

Coastal terrace deposits between Coos Bay and Bandon, north of the scenario site, are likely analogs of potential continental shelf placers (see ch. 2). Most samples taken from these deposits have contained from 6 percent to as much as 13 percent chromite, usually concentrated in the bottom 3 to 15 feet of the stratigraphic section, although samples containing as much as 25 percent chromite have been taken in some places.[18]

This scenario assumes that offshore placers contain similar grades of chromite and that the average grade is closer to 6 percent. Magnetic anomaly studies associated with surface concentrations in the scenario area suggest that the potential placer bodies lie beneath a sediment overburden that ranges from less than 3 feet to more than 100 feet thick. The ore body thickness at the mining site is assumed to be less than 25 feet.

Mining Technology.—This scenario assumes that the chromite placers are largely unconsolidated deposits and that a trailing suction hopper dredge similar to the one used in the titanium sands scenario is applicable for mining. The dredge is equipped with twin 3,400-horsepower suction pumps, giving it a greater suction capacity than the dredge used to mine titanium sands.

Dredging in rough seas at depths ranging from 150 to 300 feet will require a special design; however, it is assumed this need will not present greater technical problems or costs than, for example, building dredges or pipe-laying vessels for the North Sea. The dredge is similar in its other characteristics to the hopper dredge described in the titanium sands scenario.

At-Sea Processing.—High volumes of ore can be brought to the surface at relatively low cost, but transporting the material to shore is costly. Therefore, there is an incentive to enrich the ore as much as economically and technically feasible prior to transporting it to shore. This scenario assumes primary beneficiation at sea by a simple, low-cost process of screening and gravity separation. The system might incorporate devices such as cones, jigs, spirals, or a very large sluice box. As in the titanium

[18] LaVerne D. Kulm, College of Oceanography, *Oregon* State University, OTA Workshop on Pacific Minerals, Newport, Oregon, Nov. 20, 1986.

sand mining scenario, the effect of vessel motion on these devices needs to be evaluated. It is assumed that 30 to 50 percent of the dredged ore will be kept on the vessel and that the tailings will be continuously discharged by pipe back to the seafloor.

There are no at-sea processing plants of this type in operation. Additional investigation is needed to evaluate the feasibility and to determine the capital and operating costs of this system, but it is assumed that the development engineering required will not entail major costs.

Mining and At-Sea Processing Cycle.—Increased suction capacity plus a shorter distance to dockside and less elaborate processing at sea enable the dredge to deliver 5,000 tons of enriched ore to shore per day (rather than every third day as in the case of the titanium sands scenario). Under normal operating conditions, the dredge is assumed to take about 3 hours to fill to capacity. The vessel then steams an average distance of 75 miles for offloading at a shore facility. Transit time is estimated to average about 8 hours, offloading time less than 5 hours; hence, the vessel would be able to make one round trip per day. At dockside the dredge would be offloaded using either a dry scraper or its own pumps. Pumped transfer decreases offloading time. If this method is used, the ore is pumped into a dewatering bin and from there transported by conveyor belt to a stockpile. It is assumed that the mining and processing system can be designed so that mining and processing at sea can take place 300 days a year. This would leave 65 days for downtime due to bad weather or sea conditions, for drydocking and maintenance, and for other unforeseen events. Under these assumptions, 1.5 million tons of chromite-rich concentrate are delivered yearly to the offloading plant onshore.

Capital and Operating Costs.—Capital and operating costs (table 5-5) were estimated for mining, at-sea processing, transportation, and offloading at a shoreside facility, but not for subsequent processing on land. Capital costs amount to approximately $57 million for an operation that uses all new equipment developed for the project and built in the United States. These include a dredge ($40 million), shipboard primary beneficiation plant ($5 million), shoreside facility (about $5 million), and design, engineering, and management ($7 million). Annual operating costs are estimated to be approximately $20 million; this figure includes costs to operate the dredge and shore facility and general and administrative expenses.

Based on the above figures and assumptions, the cost of delivering enriched chromite sand to a shore-based facility was calculated. In terms of dollars per ton of beneficiated ore, the range is between $12.50 and $22. The lower cost assumes the use of a secondhand dredge. The higher cost includes a 20 percent internal rate of return which is assumed to be a realistic goal in view of the uncertainties (especially operating time) that surround the project. (If the yearly operating time were reduced to 150 days, the costs of delivering concentrates would double to between $25 and $44 per ton).

Table 5-5.—Offshore Chromite Sands Mining Scenario: Capital and Operating Cost Estimates

	Millions of dollars	
Capital Costs:		
Suction hopper dredge	$40.0	
Shipboard primary beneficiation plant	5.0	
Shoreside facility	5.0	
Engineering procurement and management (15%)	7.5	
Total	$57.5	
	New equipment (excluding profit and risk)	Used equipment (excluding profit and risk)
Annual operating costs:		
Dredge	$17	$15
Shore facility	2	2
General and administrative	3	2
Annual total	$22	$19

SOURCE: Office of Technology Assessment, 1987, Box 5-A.—Sand and Gravel Mining

Mining offshore sand and gravel is likely to be profitable at selected sites well before mining of most other offshore minerals. Sand and gravel occurs in enormous quantities on the U.S. continental shelf. However, due to onshore sources of supply in many parts of the country, the low unit value of the resource, and significant costs to transport sand and gravel long distances, profitable offshore sand and gravel mining is likely to be restricted to areas near major metropolitan centers that have depleted nearby onshore sources and/or have encountered conflicting land use problems.

Sand and gravel are currently being dredged in State waters in the Ambrose Channel between New York and New Jersey. This operation, begun 2 years ago, is the only offshore sand and gravel mining currently taking place in U.S. waters. The Great Lakes Dredge& Dock Co., the dredge operator, mines approximately 1.5 million cubic yards per year of high-quality fine aggregate from the channel. This aggregate is sold to the concrete ready-mix industry in the New York/New Jersey area at an average delivered price of $11.50 per cubic yard. The Federal Government benefits from this operation because it enables the Ambrose Channel, which is a major navigation channel into New York Harbor, to be maintained at significant savings to the government. In addition, both New York and New Jersey receive royalties of 25 cents per cubic yard of aggregate mined.

Great Lakes Dredge & Dock uses one trailing suction hopper dredge in its operation. The dredge is authorized to mine to a depth of 53 feet below the mean low water mark. When full, the dredge proceeds to a mooring point about one-half mile offshore South Amboy, New Jersey. The aggregate is then pumped to shore via a pipeline. The company estimates that there is enough sand and gravel in the channel to operate for 10 to 15 more years (longer if the channel is widened and/or deepened).

Sand and gravel mining has not yet occurred in the U.S. Exclusive Economic Zone, but the Bureau of Mines has tentatively identified two metropolitan areas, New York and Boston, where significant potential exists for the near-term development of offshore sand and gravel deposits. * Local onshore supplies are fast becoming depleted in these areas. The Bureau estimates that, for both areas, dredge and plant capital costs would range from a low of about $21 million for a 1.3-million cubic-yard-per-year operation 10 nautical miles from an onshore plant to a high of $145 million for a 6.7-million cubic-yard-per-year operation 80 nautical miles from shore. Operating costs for a product that has been screened (i.e., sorted) are estimated to range from about $3.30 per cubic yard for the smaller nearshore operation to $4.00 for the larger, more distant operation. Estimates are based on 250 operating days per year for the dredge and 323 for the plant. Other cities where offshore sand and gravel eventuality could be competitive include Los Angeles, San Juan, and Honolulu.

* An *Economic Reconnaissance of Selected Sand and Gravel Deposits in the U.S. Exclusive Economic Zone,* Open File Report 3-87 (Washington, DC: U.S. Bureau of Mines, January 1987).

There are no active facilities for processing chromite in the Pacific Northwest. Ferrochromium plants and chromium chemicals and refractories producers are concentrated in the eastern half of the country. However, one company, Sherwood Pacific Ltd., was recently formed for the purpose of constructing and operating a chromium smelter in Coos Bay, Oregon. Coos Bay has a deep draft ship channel, rail access, land, and a work force. Initial raw material for the smelter is expected to come from onshore deposits in southern Oregon and northern California.

The costs per ton of concentrate projected in this scenario allow only small margins to make and distribute a finished product, currently worth about $40 per ton. Hence, it is clear that chromite alone would not be worth recovering. Unless the price of chromite were to increase or byproducts such as gold or zircon could be economically recovered, the costs projected in this scenario do not justify economic chromite mining in the near future.

Offshore Placer Gold Mining Scenario

Location.—Gold-bearing beach sands were discovered and mined at Nome, Alaska, in 1906. Mining gradually extended inland from the current shoreline to old shorelines now above sea level. By

1906, about 4.5 million ounces of alluvial gold had been mined from a 55-square-mile area. Early miners recognized that the Nome gold placers were formed by wave action and that additional deposits, formed when sea levels were lower, should be found in the adjacent offshore area (figure 5-20).

Two U.S. companies, ASARCO and Shell Oil Co., sampled offshore deposits near Nome in 1964 and recovered alluvial gold. By 1969, proven reserves offshore of approximately 100 million cubic yards of ore had been established. The rights to these reserves were acquired in 1985 by Inspiration Resources, which then began a pilot mining and testing program. This program was followed by mining tests with a bucket ladder dredge in 1986. All operations to date have taken place within 3 miles of shore in waters under the jurisdiction of the State of Alaska, although gold resources have been identified out to about 10 miles. The future offshore gold mining operation is examined in this scenario, based on a number of assumptions.

Operational and Geological Characteristics.—Nome is a small town near the Arctic Circle on Norton Sound, a large shallow bay open to the west. Water depths in the bay do not exceed 100 feet. Ten miles offshore water is only 60 feet deep. Gold-bearing sediments are a maximum of 30 feet thick and consist of bedded sands, gravels, and clays alternating with occasional beds of cobbles and boulders. These sediments were sampled from the ice out to about 1½ miles from the coast, Gold has been found further offshore, but reserves have not yet been fully delineated. Current mining sites are located less than 1 ½ miles offshore in water depths averaging 30 feet and in formations 6 to 30 feet thick.

Only between June and October is Norton Sound ice-free and accessible to floating vessels. During the winter, thick pack ice forms over the Sound. Waves reportedly do not exceed periods of 7 seconds, but occasional sea-swells with longer periods may come from the west or southwest. Predominant winds are from the north and northeast. Currents and longshore drift are westward. Maximum tides are 6 feet.

Mining Technology.--The ***Bima,*** a bucket ladder dredge built in 1979 for mining tin offshore Indonesia, was selected to mine the offshore gold placers. The ***Bima*** was brought to Nome in July 1986 for preliminary tests. It was modified in Seattle and is scheduled to begin operation in July 1987. The ***Bima*** was designed and built abroad as a sea-going mining vessel. Its hull is 361 feet long, 98 feet wide, and 21 feet deep. The entire vessel is of steel construction and weighs about 15,000 short tons, including the dredging ladder and machinery. Freeboard is 10 feet and draft 15 feet with the ladder retracted.

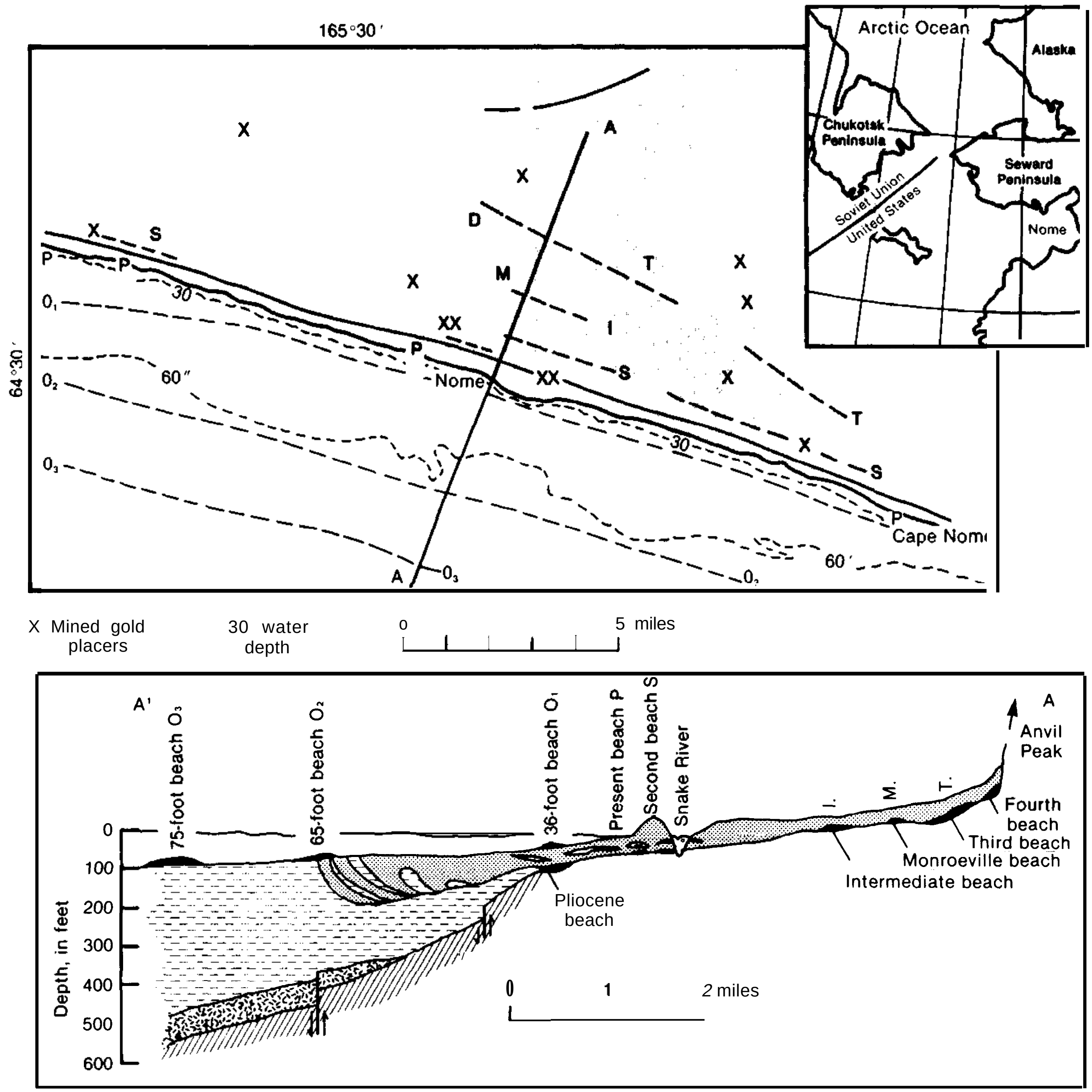
The ***Bima*** is not self-propelled. It must be moved to and from the mining site by a tugboat. On site, the dredge is kept in position by five mooring lines attached to 7-ton Danforth anchors. This anchoring arrangement allows the dredge to swing 600 feet from side to side and to advance while digging. The anchors are positioned and moved by a special auxiliary vessel.

A 15,000-horsepower diesel-electric powerplant is used to operate the bucketline, the ore processing plant, the anchor winches, and the auxiliary systems. There is fuel storage on board for 2½ months of operation.

The ***Bima's*** dredge ladder and bucketline were originally designed to operate in 150 feet of water. This scenario assumes that the dredge ladder has been shortened, so that the dredge is able to mine from 25 to 100 feet below the water line at the rate of 33 cubic yards per minute or approximately 2,000 cubic yards per hour. The ***Bima*** was designed to enable the mass of the ladder and bucketline to be decoupled from the motions of the hull by an automated system of hydraulic and air cylinders that act like very large springs. This feature keeps the buckets digging against the dredging face on the seabed while the hull may be heaving or pitching due to the motions of passing waves. During the trials of the ***Bima*** in Norton Sound from July to October 1986, it was not necessary to activate the system.

At-Sea Processing. —The ***Bima*** is equipped with a gravity processing plant to make a gold concentrate at the mining site. The throughput capacity of the plant is 2,000 cubic yards per hour, The plant consists of two parallel inclined rotary trommels 18 feet in diameter and 60 feet long. After removal of any large boulders, ore brought up by the dredge bucket slides down the trommels under the spray

Figure 5-20.— Nome, Alaska Placer Gold District



Explanation

- Alluvium
- Glacial drift
- Beach sediments
- Marine silt and clay
- Stratified rocks of unknown type
- Bedrock

Generalized geologic profile of Nome beaches.

SOURCE Adapted from E H Cobbs, U S. Geological Survey Bulletin 1374

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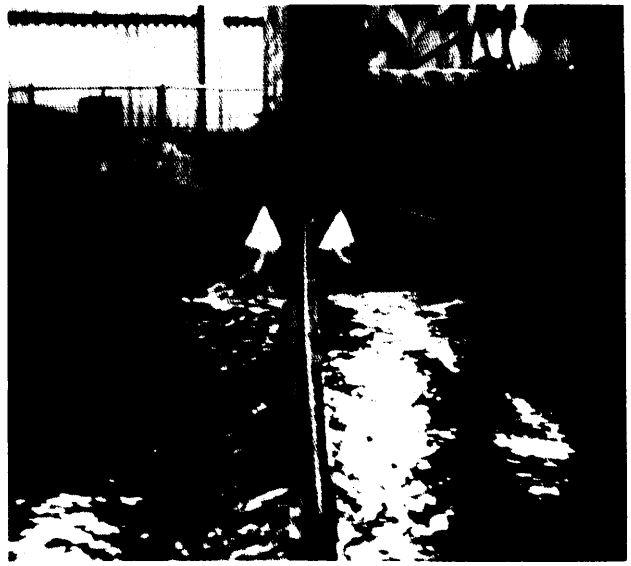

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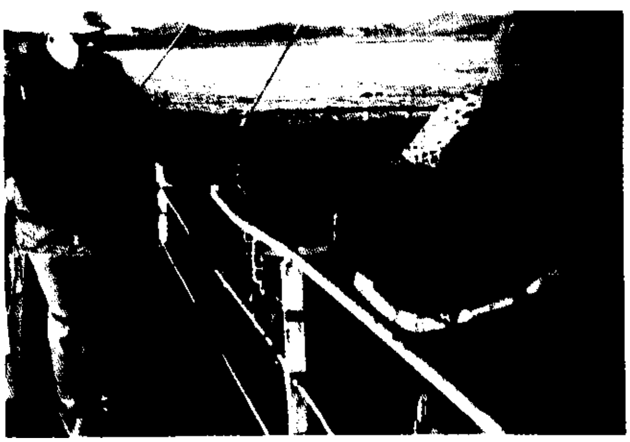

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BIMA Bucketline Dredge

Photo credit: F J Lampietti

of powerful jets of seawater. The water jets are used to break up the clay and force sand and gravel smaller than three-eighths inch to pass through the trommel. Material coarser than three-eighths inch is discharged over the stern.

Material retained by the trommel is distributed in a seawater mixture to three circuits of jigs, beginning with six primary circular jigs 24 feet in diameter. The concentrates from the circular jigs are then fed to crossflow secondary and tertiary jigs.

The jig concentrates are further refined on shaking tables before transport to shore for final gold separation and smelting into bullion. It is expected that about 22 pounds of gold concentrate will be produced by mining and processing approximately 50,000 tons of ore per day, The actual amounts of concentrate produced will depend on the quantity of heavy minerals associated with the gold at each location.

Environmental Effects.—The ore processing plant on the ***Bima*** returns 99.9 percent of the processed material to the seabed as tailings. Since the tailings do not undergo chemical treatment, local turbidity caused by particles that may remain in suspension is likely to be the most significant environmental impact. During pilot plant tests in 1985, Inspiration Resources found that turbidity could be minimized by discharging fine tailings through a flexible pipe near the seabed. Other potential environmental impacts could occur if diesel fuel is spilled, either as it is being transferred to the ***Bima*** or as a result of accidental piercing of the hull.

Operating Conditions.—The *Bima* operates only between June and October (five months per year) because ice on Norton Sound prohibits operations during the winter months. Thus, without breakdowns or downtime due to weather and other causes, a theoretical yearly production of about 7.5 million cubic yards of ore is possible. During tests in 1986, ***Bima*** operated only a small fraction of the time available. This was due more to the nature of the trials than to downtime related to winds and waves. Assuming a mining efficiency (bucket filling) of 75 percent and an operating efficiency of 80 percent (allowing for time to move and downtime due to weather), yearly production is limited to 4.5 million cubic yards. If gold grades of 0.012 to 0.016 ounces per cubic yard of ore are assumed, the yearly gold production would be between 1.75 and 2.20 short tons (before any losses due to processing and refining).

The ***Bima*** will have a crew averaging 12 persons per watch, 3 watches per day. Personnel are transported to and from Nome daily by helicopter. The operation also requires extensive maintenance, supply, and administrative facilities onshore. These facilities will be manned by an additional 46 persons during the operating season. During the winter months, the ***Bima*** will be laid up in Nome harbor, and most of the operating personnel will be on leave.

Capital and Operating Costs.—Capital and operating cost estimates (table 5-6) are based on a number of assumptions and, like the other scenarios in this report, must be considered first order approximations. The estimates rely in part on published information that the ***Bima*** gold mining project will have a life of 16 years and will recover about 48,000 troy ounces of gold per year at operating costs of less than $200 per ounce.

The ***Bima*** was constructed at a cost of $33 million in 1979. It is assumed that its purchase in 1986 as used equipment (sold because of the fall in the

Table 5-6.—Offshore Placer Gold Mining Scenario: Capital and Operating Cost Estimates

	Millions of dollars
Capital costs:	
Exploration and pilot plant mining tests	$ 3
Used dredge (BIMA)	3
Dredge transport and insurance from Indonesia to Nome	2
Shipyard modifications	5
Onshore facilities and infrastructure	2
Auxiliary vessels	2
Total capital costs	$17
Annual operating costs:	
Fuel and lubricants	$1.5
Personnel and overhead	3.0
Maintenance and spares	1.5
Services	1.0
Annual operating costs	$7.0

SOURCE” Office of Technology Assessment, 1987 price of tin) is on the order of $5 million. Also assumed is that other capital costs, including ancillary facilities onshore; pilot-plant mining tests in 1985 and trials in 1986; auxiliary vessels for prospecting and for tending anchors; shipyard modifications and alterations to the processing plant; and the cost of shipment of the ***Bima*** from Indonesia to Nome and to and from the shipyard near Seattle will amount to another $10 million to $15 million. Total capital costs are thus assumed to be between $15 million and $20 million.

Annual operating costs for fuel, maintenance, insurance and administration, and personnel and overhead are estimated (to an accuracy of 25 percent) to be $7 million. At a production rate of 48,000 ounces per year, a cash operating cost on the order of$150 to $175 per ounce is implied. At a mining rate of approximately 4.5 million cubic yards per year, direct costs would amount to $1.55 per cubic yard.

Assuming the price of gold to be $400 per troy ounce, the projected pre-tax cash flow on a production of 48,000 troy ounces per year would be approximately $12 million (after subtracting operating costs) on an investment of $17 million. Although this figure does not include debt service, it nevertheless indicates that the ***Bima*** offshore gold mining project at Nome shows good promise of profitability if the operators are able to maintain production. This scenario illustrates that offshore gold mining is economically viable and technically feasible using a bucketline dredge under the conditions assumed.

Offshore Phosphorite Mining Scenarios: Tybee Island, Georgia and Onslow Bay, North Carolina

Two different phosphorite mining scenarios were considered by OTA. The first, located off Tybee Island, Georgia, was developed by Zellars-Williams, Inc., in 1979 for the U.S. Geological Survey. The second was developed by OTA in the course of this study. Although the two scenarios differ in location and in the assumptions concerning onboard and onshore processing of the phosphorite minerals, breakeven price estimates of the two cases are well within overlapping margins of error.

Both scenarios should be considered little more than rough estimates of costs based on hypothetical mining conditions and technology. In some cases—particularly with the OTA scenario—assumptions are made about the adaptability of onshore flotation and separation techniques to at-sea conditions. Not only would additional technological development and testing be needed to adapt existing technology for onboard use, but even the feasibility of secondary separation and flotation processing at sea would also probably need further assessment and testing.

The actual costs of capitalizing and operating an offshore mining operation can vary significantly from OTA's estimates. However, in both scenarios, the results suggest that further evaluation—particularly to better define the potential resources and to consider processing technology-might be worthwhile.

While further assessment of the potential for mining phosphorite minerals offshore may be warranted, the overall condition of the domestic onshore phosphate industry cannot be ignored when evaluating the feasibility of offshore operations. The future of the U.S. phosphate mining industry seems bleak in the face of increased low-cost foreign production. Some fully depreciated mines are currently finding it difficult to meet foreign competition. New phosphate mines, either onshore or offshore, will likely find it difficult to compete with foreign operations.

If exceptionally rich phosphate resources are discovered offshore, or if offshore mining and processing systems can reduce costs through increased productivity or offsetting land use and environmental costs, the commercial prospects for offshore development might improve. However, higher phosphate prices would also be needed to make the economic picture viable, and most commodity analysts do not think higher prices are likely. Table 5-12 compares Tybee Island and Onslow Bay scenarios.

Tybee Island, Georgia

Location. —Onshore and offshore phosphorite deposits are known to occur from North Carolina to Florida. The potential for offshore mining of phosphorite in EEZ waters adjacent to the northern coast of Georgia was examined in some detail in a 1979 study by Zellars-Williams, Inc. , for the Department of the Interior. To illustrate the technical and economic feasibility of offshore phosphorite mining, OTA has drawn heavily from Zellars-Williams work.

The Zellars-Williams study considers a 30-square-mile area located about 12 miles offshore Tybee Island, Georgia, not far from the South Carolina border and in the same general area considered in the titanium scenario (figure 5-17). Only scattered, widely spaced samples have been taken in the vicinity, and none within the scenario area itself. These samples and some seismic data suggest the occurrence of a shallow phosphorite deposit in the area, but much more sampling is required to fully evaluate the deposit. The mine site is attractive for several reasons:

- water depths are uniform over the entire block, with a mean depth of 42 feet;
- the area is free of shipwrecks, artificial fishing reefs, natural reefs, rock, and hard bottom;
- the area is close to the Savannah Harbor entrance but not within shipping lanes for traffic entering the harbor; and
- an onshore plant site is available with an adequate supply of river water for process use, including washing of sea salts.

Operational and Geological Characteristics.—Average windspeed during the year at the site is about 7 miles per hour with peaks each month up to 38 miles per hour. Winter surface winds are chiefly out of the west, while in summer north and east winds alternate with those from the west. Severe tropical storms affect the area about once every 10 years and usually occur between June and mid-October. The most severe wave conditions result from strong fall and winter winds from the north and west, but the proposed mining site is sheltered by land from these directions. Waves of 12 feet or more occur about 2.5 percent of the year while 4-foot waves occur 57 percent of the year. The maximum spring tidal range is about 8 feet. Current speeds are low, about 3 to 4 miles per day. Heavy fog is common along the coast, and Savannah experiences an average of 44 foggy days a year.

Phosphorite ore occurring as pebbles and sand at the mine site is part of what is known as the Savannah Deposit. The site straddles the crest of the north-south trending Beaufort Arch, which suggests that the top of the phosphatic matrix will be closest to sea level in this area. The ore body lies beneath 4 feet of overburden. It is assumed that the ore body is of constant thickness over a reasonably large area and that the mine site contains 150 million short tons of phosphorite. The average grade of the ore is assumed to be 11.2 percent phosphorous pentoxide (P_2O_5).

Mining Technology. —An ocean-going cutter suction dredge with an onboard beneficiation plant is selected for mining. The dredge is equipped with a 125-foot cutter ladder, enabling it to dredge to a maximum depth of 100 feet below the water surface, more than enough to reach all of the mine site deposit. The dredge first removes the sandy overburden in a mine cut and places it away from the cut or in a mined-out area. Phosphate matrix then is loosened by the rotating cutter, sucked through the suction pipe, and brought onboard the dredge. The dredge is designed to mine approximately 2,500 cubic yards of phosphate matrix per hour. It is estimated that approximately 450 acres of phosphate matrix are mined each year. Mining cuts are 1 mile long and 800 feet wide.

Processing Technology.—Onboard processing consists of simple mechanical disaggregation of the matrix followed by size reduction. Oversize material is screened with trommels and rejected. Undersize material (mainly clays) is removed using cyclones. The undersize material is flocculated (thickened to a consistency suitable for disposal) and pumped to the sea bottom.

On shore, the sand size material is subjected to further washing and sizing. Tailings and clays are returned to the mine site for placement over the flocculated clays. Phosphate is concentrated to 66 percent bone phosphate of lime (BPL) by a conventional flotation sequence. The wet flotation concentrate is then blended and calcined to 68 percent BPL (approximately 30 percent P_2O_5).

It is assumed that, initially, 2.5 million short tons per year of phosphate rock are produced. Eventually, the amount produced would increase to the optimum rate of 3.5 million tons. It is also assumed that only 4 cubic yards of ore would need to be dredged per ton of final product.

Mining and At-Sea Processing Cycle.—Mining is assumed to take place 80 percent of the available time—292 days or about 7,000 hours per year. The beneficiated ore is loaded continually on 5,500 -ton capacity barges for transport to the onshore processing plant. Barge transport is deemed necessary for both economic and pollution control reasons. A tug picks up one barge at a time, taking it to a mooring point just outside the channel at the Savannah River entrance. A push boat then takes a four-barge group about 20 miles upstream to the processing facility. After the ore is discharged, the barges are reloaded with tailings sand and returned to the mooring point. The tug then returns the barge to the mining area, initially to discharge tailings and then to be taken to the dredge and left to be filled with feed.

Capital and Operating Costs.—Capital and operating cost estimates for the Zellars-Williams scenario (table 5-7) have been updated to reflect changes in plant, equipment, wages, and other cost factors. The revised figures are expressed in 1986 dollars. Capital and operating costs include costs for dredging and primary concentration, transportation of beneficiated ore to port, onshore processing to 66 percent BPL, calcining to 68 percent BPL, contingency, and working capital.

The Zellars-Williams scenario and associated costs are regarded as a "best-case' situation. 19 In 1986 dollars, the operating costs to mine and wash the ore and to transport the primary concentrate to an onshore processing plant amount to about $4.60 per short ton. Onshore processing would cost about $10 per short ton, and a depreciation expense of almost $10 per ton must be added to this figure. Hence, a "breakeven' price for calcined concentrate would be close to $25 per short ton. Calcined concentrate, however, is currently selling for only $19 to $25 per short ton, depending on grade and whether the product is sold domestically or exported. Furthermore, given uncertainties such as costs for mitigating environmental impacts, the acceptability of at-sea disposal of flocculated clays, and the uncertain effectiveness of both dredging and processing technology in the offshore environment, investors would probably require a discounted cash flow return larger than the 16.5 percent return indicated in the Zellars-Williams study. The breakeven price does not include additional requirements for profit and risk,

The largest component of total capital cost and of total operating cost is for onshore processing of the primary concentrate to 66 percent BPL, and the second largest cost component is for calcining to 68 percent BPL. Savings might be possible if an existing onshore processing plant could be used for flotation and/or calcining or if flotation at sea be-

[19] More information about the Zellars - Williams and other phosphoritc studies may be found in the OTA contractor report ' 'Offshore Phosphorite Deposits: Processing and Related Considerations, by William Harvey. November 1986.

Table 5-7.—Offshore Phosphorite Mining, Tybee Island, Georgia: Capital and Operating Cost Estimates

	Millions of dollars	
Capital costs:		
Dredging and primary concentration	$17	
Transport to port	26	
Processing to 66 percent BPL	80	
Calcining to 68 percent BPL	33	
Contingency	15	
Working capital	14	
Total	$185	
	(million $/year)	($/ton product)
Operating costs:		
Dredging and primary concentration	$ 9	$2.50
Transport to port	7	2.10
Processing to 66 percent BPL	22	6.20
Calcining to 68 percent BPL	12	3.50
Contingency	2	0.70
Total	$52	$15.00

SOURCE: Zellars-Williams, Inc., "Outer Continental Shelf Hard Minerals Leasing: Phosphates Offshore Georgia and South Carolina," report prepared for U.S. Geological Survey, May, 1979 Figures updated by OTA contractor, William Harvey comes technically and economically feasible. While there is no existing facility within a reasonable distance of the Savannah Deposit, phosphorite ore located off the coast of North Carolina (Onslow Bay) potentially could be processed at the existing onshore facility near Moorhead City.

The following scenario, developed by OTA, examines the feasibility of mining the Onslow Bay deposits, of using onboard flotation to upgrade the ore to 66 percent BPL, and of using the existing facility at Moorhead City for calcining to 68 percent BPL.

Onslow Bay, North Carolina

Location.—A high-grade offshore phosphorite resource is described by Riggs[20] and others on the continental shelf adjacent to North Carolina. The resource is located at the southern end of Onslow Bay 20 to 30 miles southeast of Cape Fear (figure 5-21). A Federal/State task force was established in 1986 to investigate the future of marine mining offshore North Carolina. The task force has hired Development Planning & Research Associates to study the feasibility of mining Onslow Bay phosphorite; however, no private companies have expressed an immediate interest in mining offshore phosphorite in this area.

The Miocene Pungo Formation is a major sedimentary phosphorite unit underlying the north-central coastal plain of North Carolina. It is mined extensively onshore. The seaward extension of the Pungo Formation under Onslow Bay has been studied using seismic profiling and vibracore sampling methods. The site selected for this scenario is where the Frying Pan Phosphate Unit of the Pungo Formation outcrops offshore in a band 1 to 2½ miles wide and about 18 miles long.

Operational and Geological Characteristics.—The site is characterized by open ocean conditions consisting of wind waves from the northeast and long period swell. Winds gusting above 30 knots occur less than 15 percent of the time. Currents are less than 1 knot and tidal influence is negligible. Hurricanes and associated wave conditions occur on an average of 10 days per year.

[20] S.R. Riggs, et al., "Geologic Framework of Phosphate Resources in Onslow Bay, North Carolina Continental Shelf," *Economic Geology*, vol. 80 (1985), p. 735.

The phosphorite formation consists of fine, muddy sands covering an area of 45 square miles. Overburden consists of loose, fine, sandy sediment varying in thickness from O to 8 feet. Underneath, the phosphorite sand has a thickness between 1 and 10 feet. Water depth averages about 80 feet; hence, the total mining depth is not expected to exceed 98 feet. The overburden contains an average of 6.3 percent P_2O_5. The phosphorite unit contains between 4.8 and 22.9 percent P_2O_5, with an average of 12.4 percent by weight.[21] Laboratory analysis of phosphate concentrates indicates the presence of no other valuable minerals.

Mining Technology.—A trailing suction dredge with an onboard beneficiation plant is selected as the most appropriate technology for the water depth and geological characteristics of the deposit. It is assumed that the phosphorite unit and overburden are sufficiently unconsolidated to be mined by suction dredging methods without the need for a cutter head. Only water jets and passive mechanical teeth are used. The dredge and plant are housed in a specially designed ship-configured hull. The vessel is not a self-unloading hopper dredge and has only a small storage capacity on board. The beneficiated ore is discharged onto barges or small ore carriers which are continuously in attendance behind the mining vessel and which shuttle back and forth to the unloading point near the shore processing plant. Dredging capacity is about 2,000 cubic yards per hour; 75 percent dredging efficiency is assumed. The suction head is kept on the seabed by a suction arm that compensates for the motion of the vessel in ocean swell. The vessel is self-propelled, dredges underway, and is equipped with precision position-keeping instrumentation.

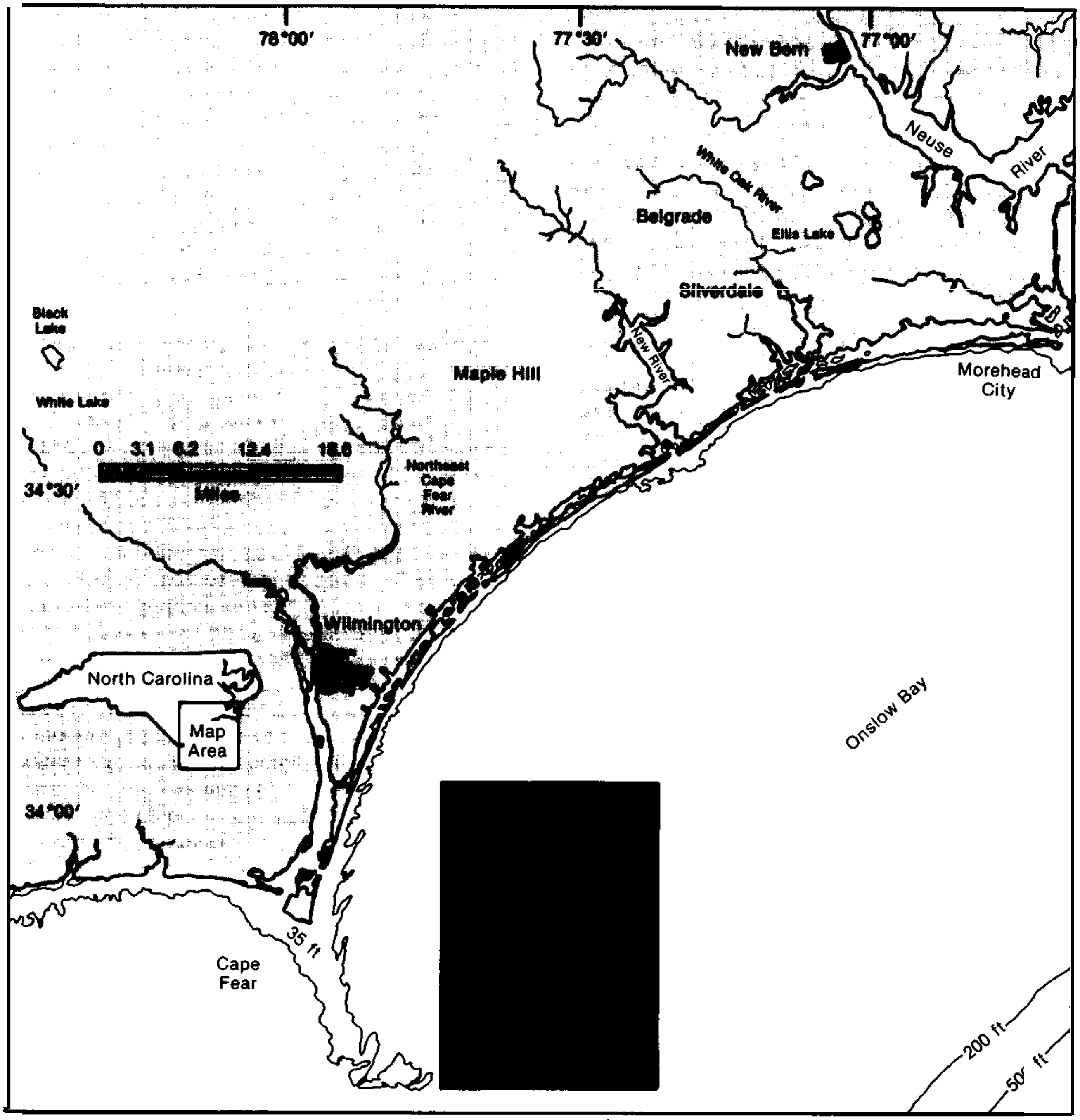
The above configuration is preferred to hopper dredging because either a very large single hopper dredge or several smaller hopper dredges would be needed to meet the mining production requirements.

Processing Technology.—At-sea processing is assumed to consist of:

- conventional mechanical disintegration and screening to eliminate oversize material,

[21] Ibid.

Figure 5-21.—Offshore Phosphate District, Southeastern North Carolina Continental Shelf



SOURCE: Adapted from S.R. Riggs, S.W.P. Synder, A.C. Hine, S.W. Snyder, M.D. Ellington, and P.M. Mallette, "Geologic Framework of Phosphate Resources in Onlsow Bay, North Carolina Continental Shelf," Economic Geology, VOl 80, 1985, p, 720.

- cycloning to reduce undersize material (e. g., clays), and
- flotation to reject silicates.

Rejected material is returned to the sea floor. The assumption that flotation can be adapted to shipboard operation requires verification by development and testing studies, the costs of which are provided for under the capital cost estimates below. The use of an existing (and, therefore, already capitalized) onshore calcining plant near Moorhead City, North Carolina, some 80 miles north of the mine site, is also assumed.

Assuming that P_2O_5 makes up 12.4 percent (by weight) of the Frying Pan unit and 6.3 percent of the overburden (both of which are mined), the mined feed to the at-sea processing plant contains 11.2 percent P_2O_5 by weight. A total of 6.9 million short tons of ore are mined each year at the dredging rate of 2,000 cubic yards per hour, yielding a shipboard concentrate of about 1.7 million tons for feed to the calcining plant onshore. This yield assumes that shipboard ore flotation upgrades the P_2O_5 content to 30 percent.

Mining and At-Sea Processing Cycle.—It is estimated that six barges, each with a capacity to carry 6,550 cubic yards of beneficiated ore, and two tugs will be required to conduct efficient and nearly continuous loading while the mining vessel is on station. The time required to load three barges, transit to shore, unload, and return to the mining vessel is expected to be 3 days. The mining vessel is assumed to operate 82 percent of the time, or 300 days per year.

Capital and Operating Costs.—The capital and operating cost estimates (table 5-8) are based on the assumption that new equipment is provided to supply beneficiated ore to an existing shore-based calcining plant. The capital costs of this shore-based plant are not included in the following estimates that may vary by as much as a factor of 2 or more.

Estimated annual operating costs are $20 per short ton. The estimated costs do not include capital recovery or the profit and risk components that would be required to attract commercial investors to an untried venture. Capital recovery alone over 20 years for a $71 million loan at a 9 percent interest rate would add an additional $8 per short ton of product, The current market price of comparable phosphate rock is about $21 per short ton. Hence, the potential for mining phosphorite in Onslow Bay would not be immediately attractive to commercial investors.

Table 5-8.—Offshore Phosphorite Mining, Onslow Bay, North Carolina: Capital and Operating Cost Estimates

		Millions of dollars
Capital costs:		
Detailed exploration, metallurgical testing and feasibility studies		$ 4
Mining and beneficiation vessel		41
Transportation to shore (tugs and barges with capacity to deliver 20,000 cubic yards every 3 days)		16
Loading, unloading, and storage installations		10
Total capital costs		$71
	(million $/year)	($/ton product)
Operating costs:		
Mining	$ 9	$ 5.00
Processing to 66°A bone phosphate of lime (BPL) offshore	12	7.00
Transport and handling	5	3.00
Calcining to 68 percent BPL (31 percent phosphorous pentoxide) onshore	8	5.00
Total operating costs	$34	$20.00

SOURCE Off Ice of Technology Assessment, 1987

Table 5-9.—Scenario Comparisons: East Coast Placer

	Bureau of Mines (January 1987)	OTA
Deposit kind	Ilmenite, rutile, zircon, etc. in old shorelines	Ilmenite, rutile, zircon, etc. in old shorelines
Grade	Approx. 5% economic heavy minerals by weight	5 to 15% total heavy minerals (economic % heavy mineral not specified)
Size	100 million short tons	Not specified
Distance to shore unloading point	80 nautical miles	100 nautical miles
Maximum dredging depth	150 feet	120 feet
Annual mining capacity—tonnage dredged	2.5 to 5.0 million short tons	3.2 to 9.5 million short tons
Mining system	Domestic built new hopper dredge with an onboard new beneficiation plant	Domestic built new hopper dredge with an onboard beneficiation plant
Mining system operating days	250	**300**
Shore processing plant	New, to produce saleable heavy mineral products	**New,** to produce saleable heavy mineral products
Capital costs (million $):		
Dredge	25.9 to 49.7	
Plant and other	16.3 to 24.5	
Total	42.2 to 74.2	55 to 86
Direct cash operating costs $U.S. per short ton dredged	4.55 to 3.79	4.72 to 2.2
Comments (OTA's)	• Technically feasible but economically marginal for heavy mineral grades assumed • No estimate of accuracy of scenario • Costs most sensitive to distance from shore	• Accuracy of scenario not estimated • Costs most sensitive to heavy mineral grade

SOURCE: Office of Technology Assessment, 1987.

Table 5-10.—Scenario Comparisons: West Coast Placer

	Bureau of Mines (January 1987)	OTA
Deposit kind	Chromite with minor titanium, zircon, and gold	Chromite with insignificant amounts of ilmenite, rutile, and gold
Grade	>6% Cr_2O_3 + .0048 oz. Au per short ton	6°/0 Cr_2O_3
Size	.50 million short tons	Not specified
Distance to shore unloading point	40 nautical miles	75 nautical miles
Maximum dredging depth	150 feet	300 feet
Annual mining capacity—tonnage dredged	5,000,000 short tons	4,500,000 short tons
Mining system	Domestic built new hopper dredge	Domestic built new hopper dredge
Mining system operating days	250	300
Shore processing plant	New, to produce saleable mineral products	New, to produce saleable mineral products
Capital costs (million $):		
Dredge	41.4	40.0
Plant and other	44.3	17.0
Total	85.7	57,0
Direct cash operating costs $U.S. per short ton dredged	5.42	**4.00**
Comments (OTA's)	• Technically feasible but economically marginal for heavy mineral grades and prices assumed • No operating experience • No estimate of accuracy	• Technically feasible but economically marginal for heavy mineral grades and prices assumed Ž No operating experience • No estimate of accuracy

SOURCE Off Ice of Technology Assessment, 1987

Table 5-11 .-Scenario Comparisons: Nome, Alaska Gold Placer

	Bureau of Mines (January 1987)	OTA
Deposit kind	Gold Placer	Gold Placer
Grade	0.6 gram per $yard^3$	0.35 to 0.45 gram per $yard^3$
Size	35,000,000 $yard^3$	80,000,000 $yard^3$
Distance to shore unloading point	0.5 to 5 miles	0.5 to 10 miles
Maximum dredging depth	80 feet	90 feet
Annual mining capacity—tonnage dredged	1,632,000 yd^3	4,500,000 yd^3
Mining system	Used seagoing bucket line dredge with full gravity processing	Used seagoing bucket line dredge with full gravity processing
Mining system operating days	150	150
Shore processing plant	Minimal for final cleaning of gold concentrates	Minimal for final cleaning of gold concentrates
Capital costs (million $)		
Dredge		5
Plant and other		10-15
Total	$9.1	15-20
Direct cash operating costs $U.S. per $yard^3$ mined	2.00	1.55
Comments (OTA's)	• Technically feasible and appears economically profitable	. Technically feasible and appears economically profitable

SOURCE" Off Ice of Technology Assessment, 1987

Table 5-12.—Scenario Comparisons: Onslow Bay and Tybee Island Phosphorite

	Zellars-Williams (Tybee Island) (updated 1986)	OTA (Onslow Bay)
Deposit kind	Pebbles and sand	Sands
Grade	11.1 percent P_2O_5	11.2 percent P_2O_5
Size	150 million short tons	Not specified
Distance to shore unloading point	30 miles	80 miles
Maximum dredging depth	100 feet	98 feet
Annual mining capacity—tonnage dredged	2.5-3.5 million short tons	6.9 million short tons
Mining system	Ocean-going cutter suction dredge with onboard screening and cycloning	Trailing suction hopper dredge; onboard screening, sizing, and flotation
Mining system operating days	292 days	300 days
Shore processing plant	Washing and sizing, flotation, calcining	Calcining only
Capital costs (million $)		
Dredge & offshore processing	$ 17	$ 41
Transportation to shore	26	16
Onshore processing	113	—
Other	29	14
Total	$185	$ 71
Cash operating costs $U.S. per short ton	$ 25	$ 28
Comments (OTA's)	• Cash operating cost is break-even; Does not include profit and risk. • Estimate considered "best case." • Estimate may be off by factor of two or more.	• Cash operating cost is break-even; Does not include profit and risk. • Does not include capital costs of existing onshore calcining plant. • Estimate may be off by factor of two or more

SOURCE: Office of Technology Assessment, 1987