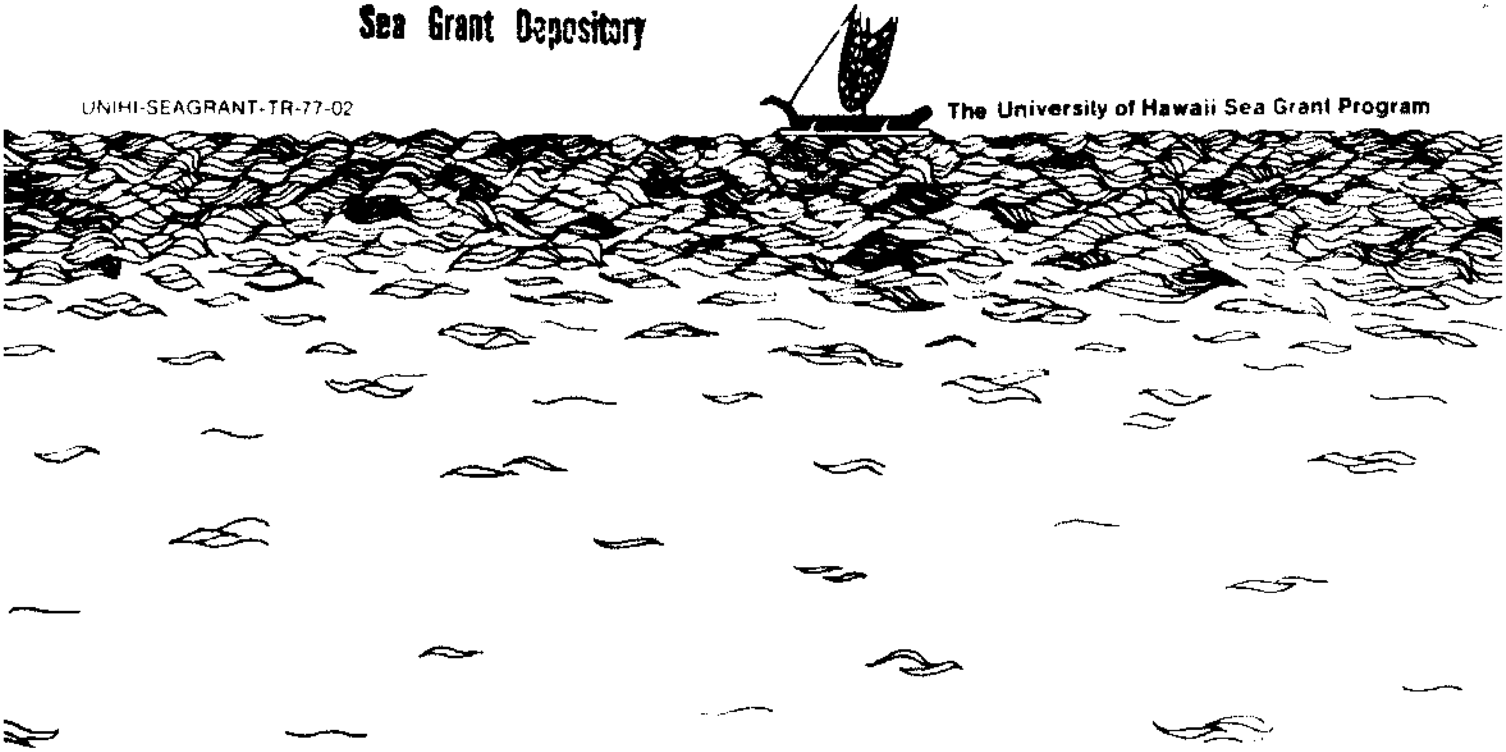
UNIHI-SEAGRANT-TR-77-02

The University of Hawaii Sea Grant Program



Submarine Sand Recovery System

Keauhou Bay Field Test

Frederick M. Casciano

September 1976

SUBMARINE SAND RECOVERY SYSTEM: KEAUHOU BAY FIELD TEST

by

Frederick M. Casciano

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ABSTRACT

A small portable ocean sand mining system developed under the Sea Grant Program was field tested near Keauhou Bay, Hawaii using state and local industry matching funds. The purpose of the tests was to assess the technical, environmental, and economic feasibility of the system for beach restoration and other commerical applications.

About 12,000 cu yd of sand were recovered from a 20-ft thick sand pocket located amidst a flourishing coral reef and discharged to a basin on shore through 1400 ft of 6-inch plastic pipe.

The basic component of the system, the suction probe, burrows beneath the sand surface to extract sand; it was found to function well to an overall depth of 85 ft and in seas of up to 6 ft. The system can be operated with a crew of two, achieving a slurry of up to 35 percent sand by volume with an average production rate of about 48 cu yd/hr.

Although the probe created more turbidity than had been expected, due to the way in which sand collapsed into the craters, there appears at first glance to have been no detrimental effects to the environment due to turbidity. A summary of a more complete environmental assessment is included as an appendix to this report.

The projected costs for sand produced by this system are estimated at between $3.00 and $5.50 per cubic yard, depending upon the volume to be recovered.

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INTRODUCTION

In 1968, the University of Hawaii, funded by the National Sea Grant Program, initiated a study to determine the extent and location of offshore sand deposits around the Hawaiian Islands and to investigate the feasibility of exploiting this resource to supplement or replace land sources. Exploration showed that vast quantities of sand do indeed exist off the shores of many of the islands, but several factors appeared to stand in the way of the successful utilization of these deposits. Such problems as environmental disturbance, legal and economic uncertainties, and difficulties encountered using conventional dredges at sea presented the most serious deterrents. The "Sand Recovery" project sought to develop technology which might alleviate some of these problems.

A somewhat unique system was designed for operation in thick sand deposits from a small vessel with minimal crew; it could be used in fairly heavy seas without the sophisticated control equipment required on large ocean-going hydraulic dredges. Furthermore, the mining technique to be utilized--that of burying a suction head beneath the sand surface--would hopefully reduce turbidity and the risk of physical damage to coral, both of which would otherwise present the greatest threat to the Hawaiian marine environment.

The Submarine Sand Recovery System (SSRS), as this new system is called, was model tested on a scale of 1:12 at Look Laboratory of Oceanographic Engineering; half-scale and full-scale models were ocean tested. Various modifications were incorporated into the prototype which was sized for use with a 6-inch pump and which was put through preliminary ocean tests in November 1972.

In order to successfully complete the project, it was desired to subject the prototype to a full-scale long-endurance test simulating possible future commercial sand operations. The objective of the test was to transfer at least 10,000 cu yd of sand to shore such that the performance of the system could be assessed with regard to the design objectives: that is, could it operate without causing significant damage to the environment; could it operate in a seaway without major failures and downtime; and in general, would the technique and scale of operation permit economical recovery of sand from the ocean?

Such a test was conducted near Keauhou Bay on the Kona coast of the island of Hawaii in the latter part of 1974. This report covers the operational and technical aspects of that experiment. An environmental monitoring program was carried out by Sea Grant under the direction of Dr. James Maragos. A summary of the results is in Appendix A.

This report is a follow-up to the University of Hawaii Sea Grant advisory report, *Development of a Submarine Sand Recovery System for Hawaii* (UNIHI-SEAGRANT-AR-73-04), which describes the early work.

PERMITS AND THE LAW

The legal/environmental problems of conducting such a test were formidable. In 1968, when the project began, it was legally permissible to mine sand from the offshore waters in Hawaii as long as permits were obtained from state, county, and federal agencies having jurisdiction. The state policy then was to issue permits only in areas where the water depth was greater than 50 ft. However, the 1970 Hawaii State Legislature, by Act 136 which concerns shoreline setbacks, inadvertently made such mining illegal in state waters.

Commencing with the 1972 legislative session, efforts were made through the University of Hawaii Sea Grant College Program and the State Office of the Marine Affairs Coordinator to change the law to permit controlled taking of sand in certain offshore areas. Later, in February 1973, permit applications were initiated to conduct field testing of the SSRS near Keauhou Bay, Hawaii at some 300 to 600 ft off a rockbound coast in water depths of from 50 to 70 ft.

In the spring of 1973, the State Legislature passed Act 107 which qualified the earlier prohibition and made it illegal to remove sand only in areas within 1000 ft of the shoreline or in water depths of 30 ft or less. The subsequent interpretation of this act required that both the 1000-ft and 30-ft conditions be met simultaneously. This ruling resulted in the State Department of Land and Natural Resources' denial of the University of Hawaii's pending permit application and seemed to place much potentially usable sand around Hawaii out of legal bounds with any apparent scientific basis.

House Bill 2276-74 was introduced in the 1974 legislative session to clarify the interpretation of Act 107 to allow mining where either the depth of water criterion or the distance criterion is met. This was particularly desirable for the island of Hawaii where deep water is a short distance off shore--in many areas water depths of 100 ft or more are found within 1000 ft from shore. Unfortunately, the bill was defeated.

Finally, an amended version of H.B. 2276-74 was passed and signed into law as Act 79. It specifically exempted the University of Hawaii from the depth/distance prohibitions for the purpose of conducting the SSRS experiment at Keauhou.

However, before tests could be conducted, an environmental impact statement (EIS) was required by the U.S. Army Corps of Engineers. A study of the expected impact was made during the summer of 1973 and an environmental statement was completed in September 1973. From this the National Sea Grant Program office prepared the draft EIS issued in February 1974. The final EIS was approved in August 1974. In all, permits were obtained from the U.S. Army Corps of Engineers, the State Department of Land and Natural Resources, the State Department of Transportation's Harbors Division, and the County of Hawaii. The first two permits took approximately 18 months to process, primarily due to the impact statement preparations and processing and the legal confusion.

DESCRIPTION OF THE SSRS

The SSRS is a lightweight portable sand pumping outfit designed to be placed aboard a small barge or boat without requiring major modifications to the vessel. The system is capable of pumping an average of 50 to 60 cu yd of sand per hour in a slurry having a sand content of from 20 to 30 percent by volume. Designed chiefly for direct pumping to shore via a submerged plastic pipeline of up to 2000 ft without boosters, it can be operated by a two-man crew once it is set up. The sand/water mixture is set by an essentially fixed sand/water inlet ratio, but adjustments can be made from deck via a hydraulically operated sand inlet valve.

Since the suction head does not have to be lifted off the bottom continually to control the sand percentage as with conventional hydraulic systems, there is no requirement for a rigid coupling between the surface vessel and the head. Flexible hose can be used between the pump and suction head--essentially isolating the head from the motions of the vessel.

The system is effective only in relatively thick deposits of sand such as 25 to 50 ft since its method of operation requires that the suction head, or suction probe as it is called here, be buried in the sand and moved as infrequently as possible. As sand is drawn into the buried head, a crater in the shape of an inverted cone is formed: the thicker the sand, the larger the crater, and obviously the greater the volume of sand that can be removed from each probing. This type of system results in less chances of direct physical damage to coral reefs than would be likely from a trailing suction dredge and is believed to cause less turbidity than mechanical dredges, such as a clamshell and bucket ladder, as well as some suction dredges which strip away the bottom in layers. Courtenay et al. (1972) described reef damage observed in Florida as the result of sand dredging operations with a conventional suction dredge.

Components

The major component of the SSRS is the suction probe which is shown in some detail in Figure 1. It is approximately 15 ft long and made up of two 6-inch steel tubes leading side by side into a mixing box. The mixing box has a specially designed, hydraulically operated roller crusher bolted to the top plate between the steel tubes and a jetting nozzle (check valve) which is attached to an opening in the bottom (see Figures 2 and 3).

A square opening in the top plate--the sand inlet--is fitted on the underside of the plate with a sliding vane valve which is operated by a rack and pinion gear. The pinion is rotated by a hydraulic rotary actuator mounted at the top end of the probe via a long shaft made from 1/2-inch pipe. (See the diagrams in Figure 4.)

Between the tubes and above the crusher is a 6-ft long, 16-inch diameter, fixed flotation tank made of polyurethane foam wrapped with fiberglass. Removable arms are attached to the outer faces of the tubes

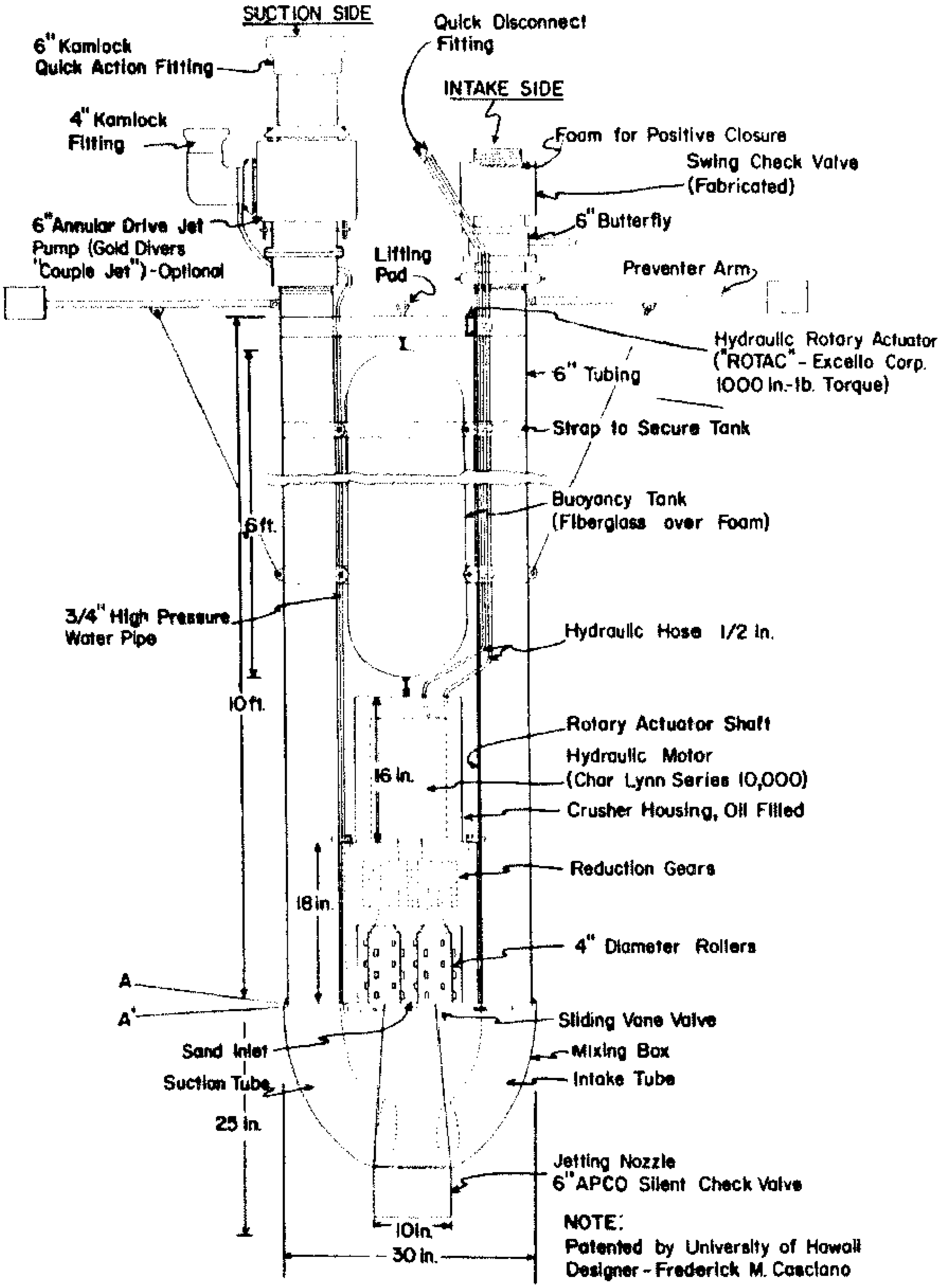


Figure 1. Schematic diagram of the suction probe

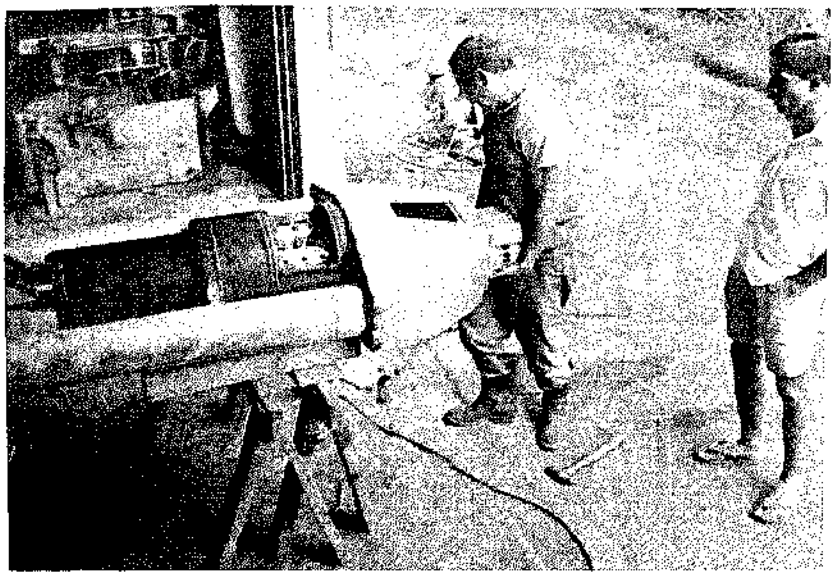


Figure 2. Assembling the suction probe

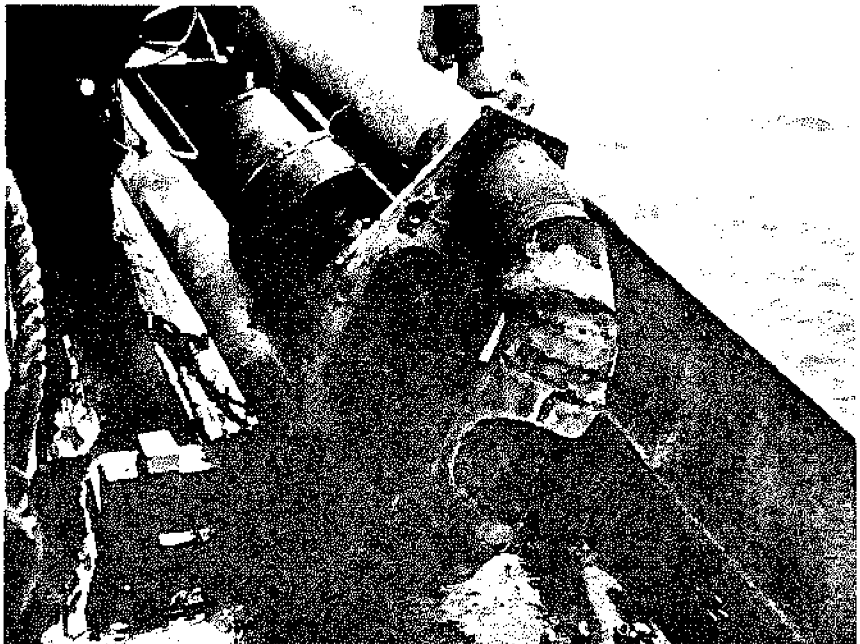


Figure 3. Inside view of the mixing box

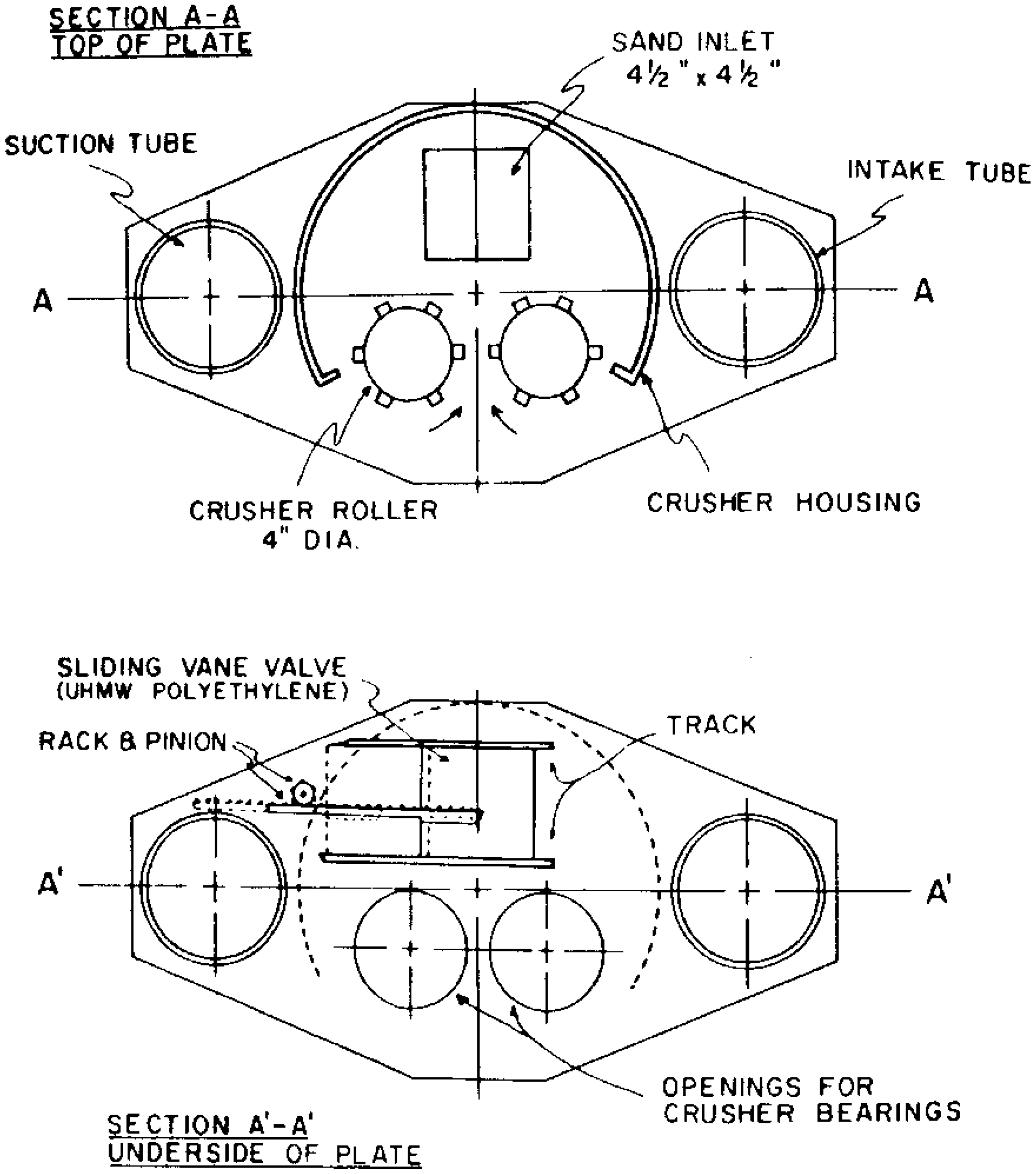


Figure 4. Top plate of mixing box

near the top. These, called preventer arms, serve to keep the probe from burrowing too far into the sand during jetting.

Additional components of the system which attach to the probe are shown in Figure 5. They include:

- two buoyancy tanks--one essentially fixed and one variable
- a 6-inch jet pump (Gold Divers, Inc., Los Angeles, California) which mounts on top of the suction probe when needed in deep water as an assist
- flexible 6-inch and 4-inch plastic hoses
- 1/2-inch and 3/8-inch hydraulic hoses
- fluidizing pipe

The remaining components which are mounted on the barge overhead consist of:

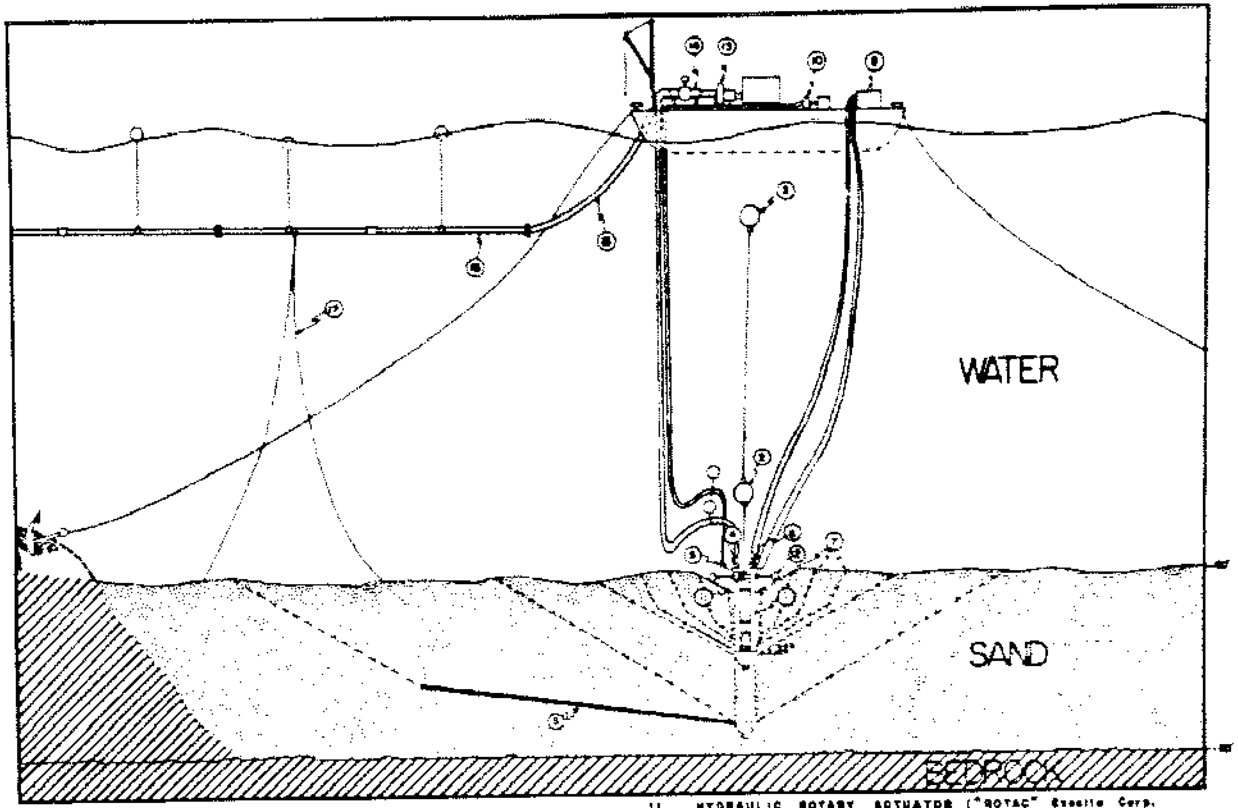
- a 6-inch sand pump (AMSCO Wearmaster BRB form 20 materials handling pump, ABEX Corp., Chicago Heights, Illnois; powered by a 200-hp Continental diesel)
- a 6-inch valving manifold
- a 4-inch auxiliary water pump (model 64A2B, Gorman-Rupp Co., Mansfield, Ohio; powered by a 45-hp GM-2-71 diesel) providing drive water for the jet pump, for the fluidizing pipe, and for priming the 6-inch sand pump
- a boom and winch for lifting the hose aboard
- a hydraulic power unit (ROTAC Excello Corp., Greenville, Ohio) with directional control valves for operation of the roller crusher, rotary actuator, and winch

The system is completed with the means of delivering the sand ashore made up of a 6-inch schedule 40-PVC pipe suspended below the water surface by plastic buoys. (Note: A U.S. patent on the system has been obtained by the University of Hawaii.)

Operation

The system is operated by placing the suction probe in the water as shown in Figure 6 and adjusting the buoyancy in the variable buoyancy tank so as to allow the probe to sink to the bottom while maintaining a rigid vertical altitude. Water from the 6-inch pump is directed downward to the probe through the 6-inch hose while suction is taken through a short pipe leading overboard. Suction and discharge flow directions are controlled by the valving manifold. The flow emanates from the jetting nozzle and is prevented from escaping through the crusher and intake tube by the sliding vane valve and check valve on the top of the tube. The jetting action buries the probe into the sand until the preventer arms strike the firm sand outside of the jetting hole, at which time downward motion ceases.

Suction is then taken on the 6-inch hose and thus from the suction tube of the probe by means of the valving manifold and the discharge is directed to shore. Water flows down the intake tube through the mixing box and up the suction tube. Sand enters the system upon activation of



1 SUCTION PROBE
2 FIXED BUOYANCY TANK
3 VARIABLE BUOYANCY TANK
4 SUCTION TUBE
5 JET PUMP -- 6" eductor-jet (Gold Diver's Inc. Los Angeles, California)
6 INTAKE TUBE
7 SUCCESSIVE CRATER WALLS
8 FLUIDIZING PIPE
9 HYDRAULIC POWER UNIT
10 4" PUMP -- model 84A2B (Gorman - Rupp Co. Mansfield, Ohio)
powered by a 45 hp GM-3-71 diesel
11 HYDRAULIC ROTARY ACTUATOR ("ROTAC" Excello Corp. Greenville, Ohio)
12 PREVENTER ARMS
13 6" PUMP -- AMSCO Wearmaster SRB form 20 materials handling pump (ABEX Corp., Chicago Heights, Ill.)
powered by a 200 hp continental diesel
14 VALVING MANIFOLD
15 FLEXIBLE HOSES
16 8" SCHEDULE 40 PCV PIPE
17 PIPELINE ANCHOR LINES

Figure 5. SSRS suction probe and components in operation

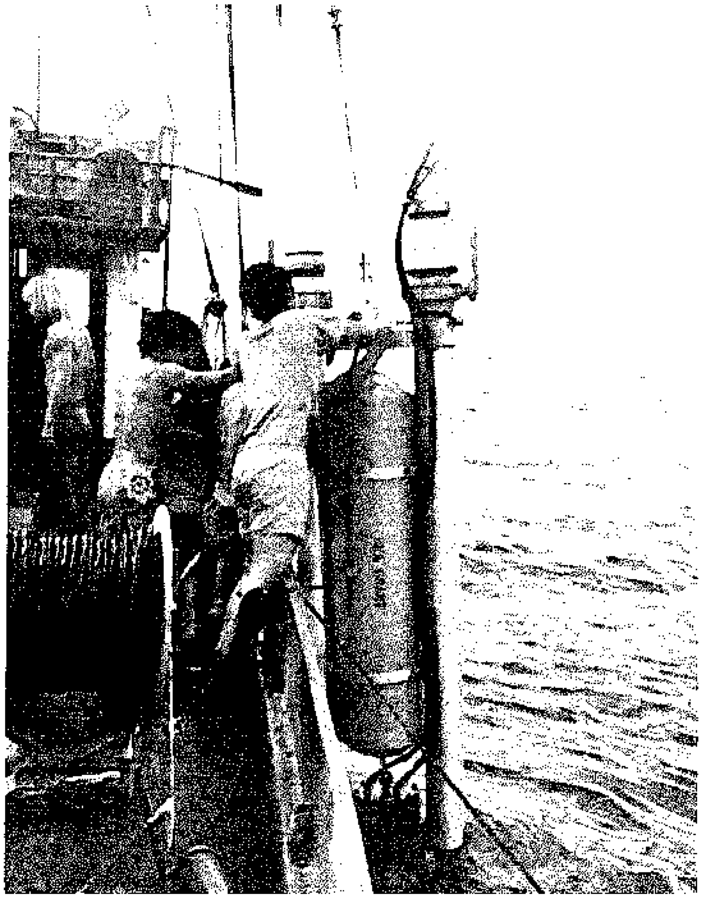


Figure 6. Lowering the suction probe over the side of the *Valiant Maid*

the rotary actuator which opens the sliding valve at the sand inlet. The roller crusher is similarly activated by hydraulic power. Sand, along with shells, rocks, and dead coral pieces, must pass between the rollers before entering the mixing box, in order to reduce the size of the chunks sufficiently to pass through the 6-inch system. The rollers rotate slowly, at about 15 rpm, but can exert 25,000 inch-pounds of torque--an amount sufficient to crush most materials which are likely to be found mixed in the sand.

Sand is drawn into the mixing box where it forms a slurry and is carried up to the pump. This continues until a stable-walled crater is formed, generally with side angles of 30 to 35 degrees. The angle varies to some extent with the grain size of the material.

At this point the probe is jetted in another increment and the process repeated until the bottom of the deposit is reached. As the probe buries deeper in the sand, each increment produces considerably more sand than the previous one.

The approximate volume obtainable for various sand depths, assuming a 32 degree angle of repose, is shown in Table 1.

TABLE 1. APPROXIMATE SAND VOLUME OBTAINABLE ACCORDING TO CRATER SIZE FOR VARIOUS DEPTHS OF SAND PENETRATION

Sand Depth (ft)	Diameter of Crater (ft)	Volume of Sand (cu yd)
10	32	100
20	64	795
30	96	3,690
40	128	6,360
50	160	12,400
60	192	21,420
70	224	34,100
80	256	51,000

Sand flow into the mixing box can be reduced or shut off almost instantaneously from deck with the directional control valve on the hydraulic power unit, which controls the fluid to the rotary actuator. Thus, the entire length of suction and discharge lines can be flushed with clear water when desired, and the probe can be left buried in the sand when securing for the night.

When the supply of sand from any probe station is exhausted, the probe is removed by increasing the buoyancy while jetting. The probe lifts out of the hole and arrives at equilibrium when the top float hits the surface, with the jetting nozzle a few feet off the bottom. The probe can now be readily moved--by a diver during the testing--and re-implanted nearby. Another option--that of increasing the volume of sand obtained from each crater through the use of a "fluidizing pipe" will be discussed in the section on description of the operation.

A lightweight jet pump, or educator, is mounted on the top of the intake tube to provide additional lifting power in deep water.

TEST SITE

The island of Hawaii or the "Big Island" is the youngest in the Hawaiian chain; so young that its coastline is still being changed by lava flows from active craters on Mauna Loa. Because of this, the island has few good beaches, although large deposits of reef-generated calcareous sand appear to exist offshore. Since there is no land source of calcareous sand here, sand for beach building or restoration must be brought in from other islands. Shipping and handling costs are so prohibitive--unit costs are roughly $20 to $30 per cubic yard--that importing beach sand is rarely done. Instead, sand for construction is taken from lava rock quarries on the island. Because of these conditions, this island was considered to be a fertile location for the prospect of ocean sand mining and, therefore, a prime area to conduct the experiments.

The test site was located about six miles south of Kailua and a half mile north of Keauhou Bay as shown in Figure 7. The ocean bottom in the area consisted of widely separated pockets of sand situated between beds of coral and rock. The pocket chosen for the tests was almost completely surrounded by coral. It began some 300 ft from shore in 50 ft of water, extended to 1000 ft from shore in 90 ft of water, and was a maximum of 500 ft wide. Only the inshore section of the deposit, to a water depth of 65 ft, was set aside for mining. The sand here was a maximum of 25 ft thick. (See the plan view in Figure 8.)

Initial surveys showed that sand grain size was fairly uniform on the surface with the exception of an area of coarser sand at the south end of the pocket. The average grain size of the larger body of sand was 0.15 mm, consisting of 2 percent coarse sand, 8 percent medium sand, 55 percent fine sand, 32 percent very fine sand, and 3 percent silt. A distribution curve of a typical surface sample is shown in Figure 9. The sand had a light grey color which seems to typify underwater deposits in Hawaii. Chemical analysis indicated that the sand was 25 percent basalt and 75 percent calcium carbonate. Nutrient and trace element analyses indicated normal levels as compared with other submarine sand samples taken from around the islands. Although no grain size analysis of samples from the mining was conducted, the sand appeared to be relatively uniform with depth beneath the surface; however, it was noticed that the sand became finer overall as mining moved to deeper water.

Wave conditions in the area are most severe during the winter season, but were expected to be less than 10 ft 97 percent of the time and less than 4 ft 50 percent of the time. Although several periods of high waves producing 8 to 12-ft surf along the shore were encountered during the tests, the seas were never more than 6 ft at the barge. Surface and bottom currents in the area were found to be very weak and generally southerly setting during initial surveys, but during the tests, currents from 1/2 to 1 knot were experienced on occasion.

The coastline directly shoreward of the site is composed of rugged lava rock with a vertical elevation of about 15 to 20 ft (Figure 10). The nearest beach, about a mile away at Kahaluu Beach Park, is very small and protected by a shallow outside reef.

The site fronts the Keauhou-Kona golf course managed by Kamehameha Development Corporation (KDC), a company that has been developing Bishop Estate land in the area as a resort community. This corporation provided matching funds and other support for the experiment which included the construction of a deposition basin and settling pond on its land. In return, it hopes to purchase the recovered sand from the state at a reasonable cost for use at a small public beach in Keauhou Bay and for golf course construction and maintenance.

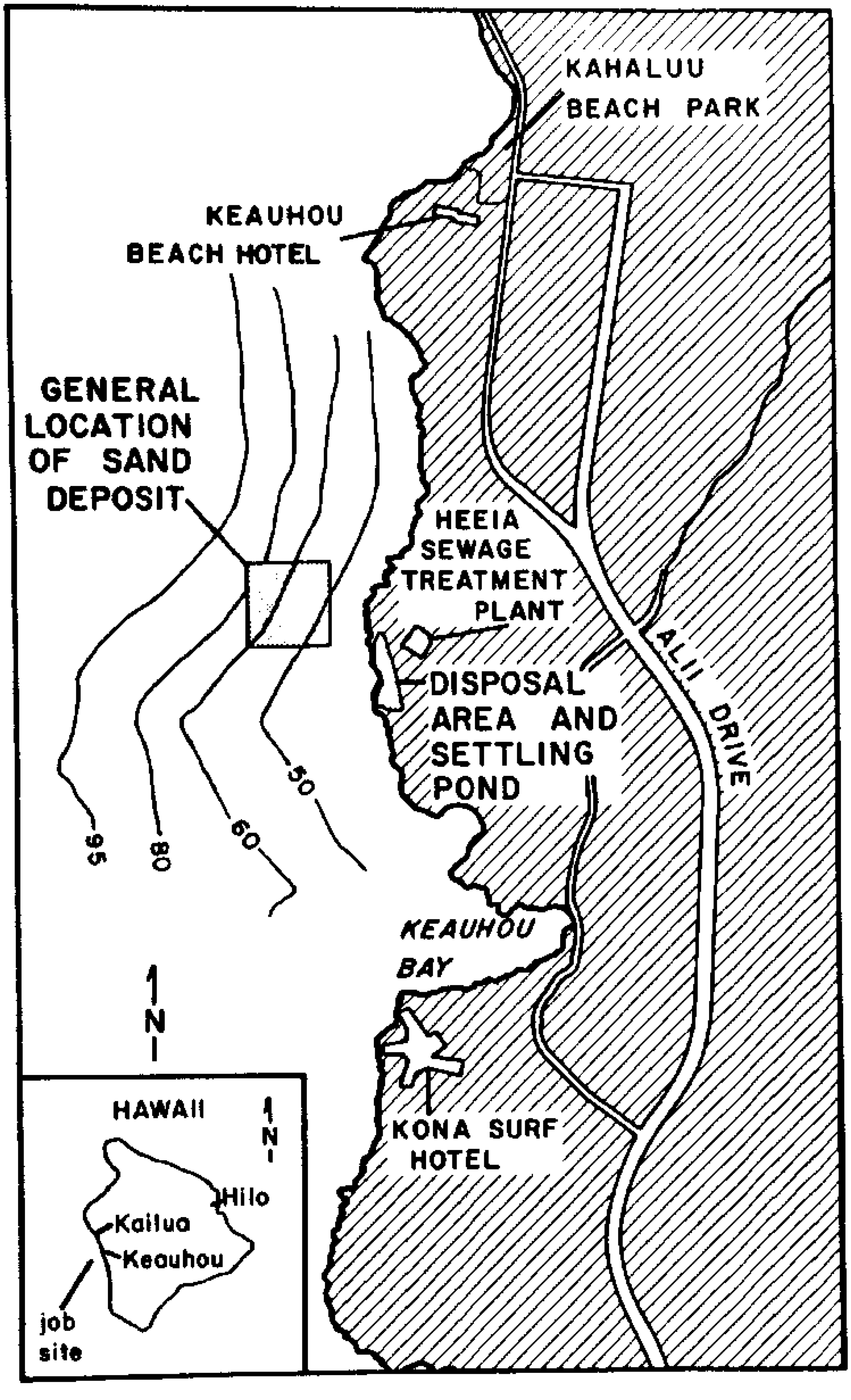


Figure 7. Map showing location of test site

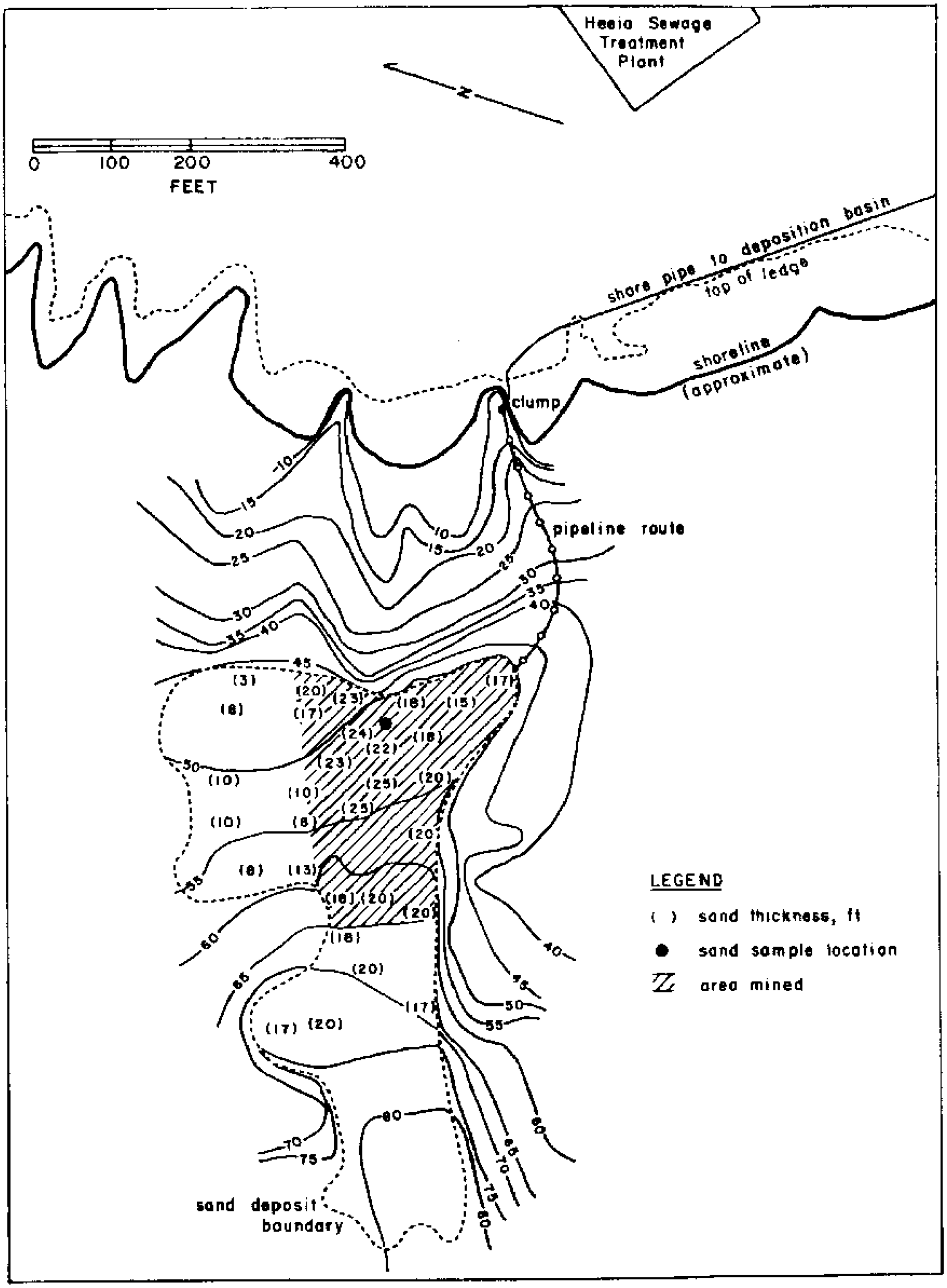


Figure 8. Sand deposit location and bathymetric after mining

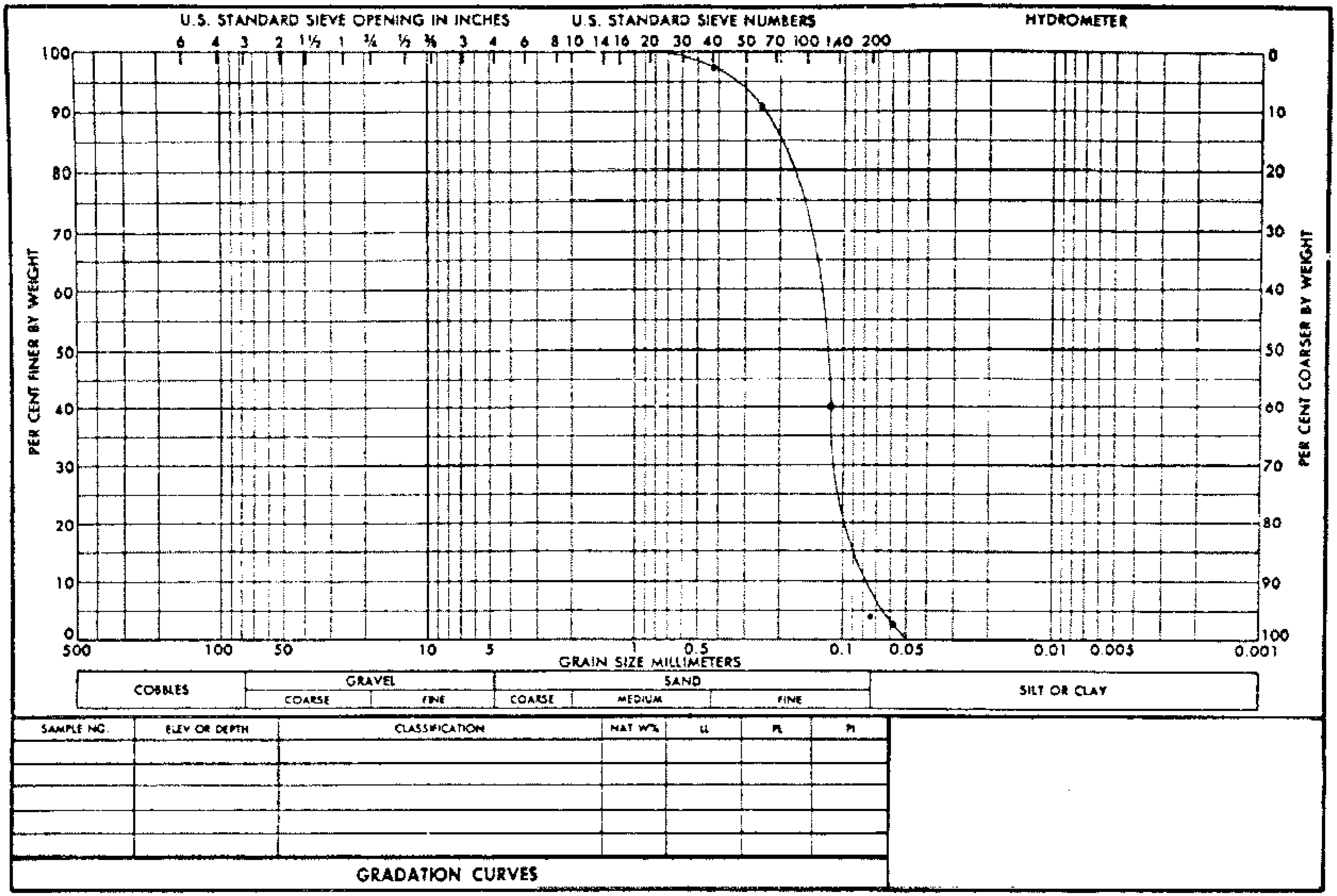


Figure 9. Gradation curve of surface sand sample

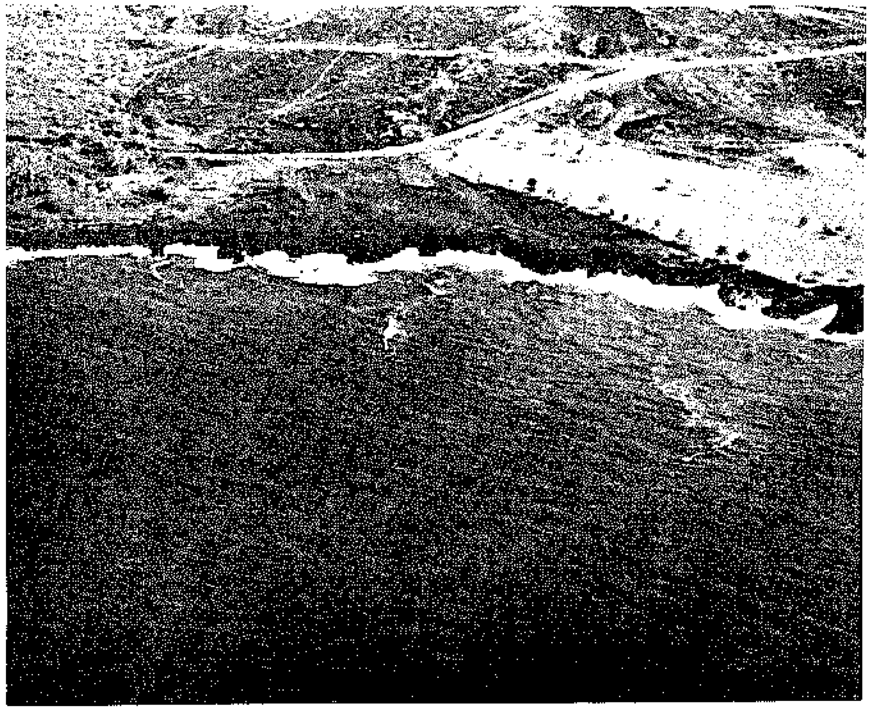


Figure 10. Aerial view of test site

DESCRIPTION OF THE OPERATION

Time Frame

The field operations from beginning to end took 3 months and 18 days. The following dates catalog the events and are useful in observing relative time spans.

8/18/74	5-man team (3 University personnel, 2 boat crew) departed Honolulu on the *Valiant Maid*
8/18/74 to 8/24/74	At Kawaihae, Hawaii, prepared and launched barge; outfitted it with sand mining equipment
8/25/74	Barge and *Valiant Maid* anchored off Keauhou Bay
8/26/74 to 9/05/74	Discharge and settling ponds completed on shore; pipeline assembled and layed from barge to discharge area
9/06/74	Commenced pumping sand
10/07/74 to 10/17/74	Shut down while overhauling engines and modifying suction probe; crew reduced to four men
11/21/74	Ceased sand pumping

11/22/74 to 11/30/74	Disassembled equipment; removed pipe, anchors, etc., and restored area to as near original conditions as possible
12/01/74	Departed Keauhou Bay on *Valiant Maid* with barge in tow
12/02/74 to 12/03/74	At Kawaihae, returned barge to shore storage
12/04/74	Returned Honolulu

Barge and Tender Vessel

A 30 ft long x 16 ft wide non-self-propelled catamaran barge was leased from dry storage at Kawaihae, Hawaii. The deteriorated hull was scraped and painted and placed in the water with forklifts. Equipment was mounted at dockside. Figure 11 shows the barge after launching and Figure 12 shows pump trials being conducted.

The barge was towed to the Keauhou test site by the 56-ft fishing/research vessel, *Valiant Maid*, and then anchored in a five point moor over the sand deposit using a 700-lb Danforth anchor at the head and four smaller anchors at the corners. It was located over each probe by manually hauling on the anchor lines. This proved to be tedious in strong winds, but fortunately the barge was not moved frequently--on the average of once a week.

The *Valiant Maid* served as the tender throughout the experiment. This vessel carried the suction probe and most of the supplies and support components. It was equipped with a 2-ton capacity boom and winch for deploying the suction probe and was used during the tests to fuel the barge periodically, lay the pipeline, and move anchors when necessary.

Pipeline

Lengths of 6-inch schedule 40-PVC pipe were glued together to form 40-ft sections with flanges at each end. The glue joints were further reinforced with four 1/4-inch cap screws around the circumferences of each joint. The sections were light enough to be carried by two or three men and could be handled easily aboard the *Valiant Maid*. (See Figure 13.) The pipe was layed from the barge to shore (initially about 400 ft) and along shore to the deposition basin (another 600 ft).

The sea pipe was suspended 12 ft beneath the water surface by 19-inch diameter plastic buoys (Jim Buoy) placed every 20 ft along the pipeline such that each 40-ft segment was stable in the water and could be unbolted and floated free if replacement were required. This sub-surface suspension technique was chosen to reduce wave forces on the pipe from that which would be experienced on the surface, to keep the pipeline off the bottom where chafing might occur against coral heads--possibly damaging both, and to allow small boats to pass over the pipeline unhindered.

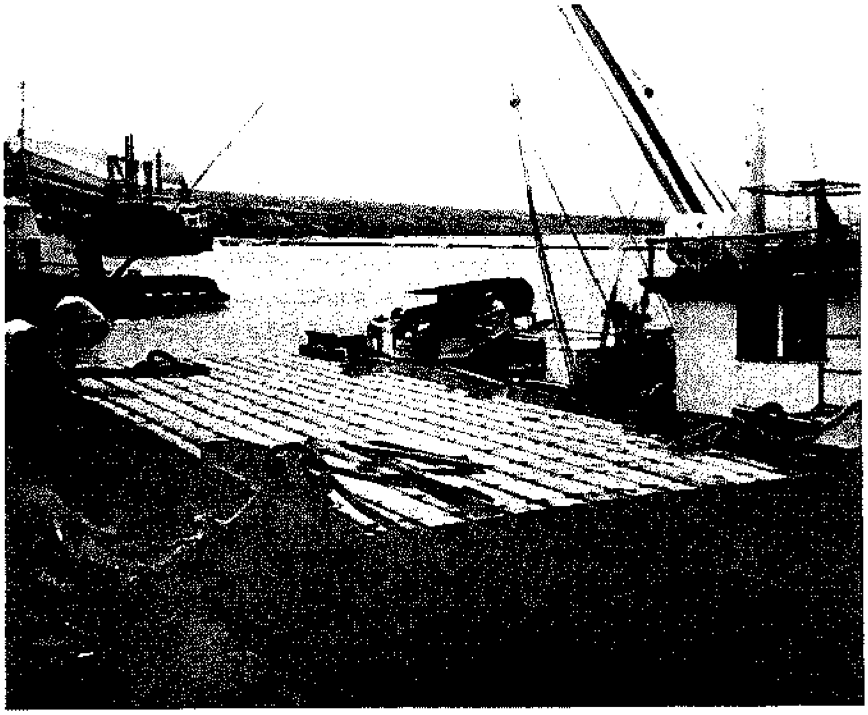


Figure 11. Bare barge alongside *Valiant Maid*

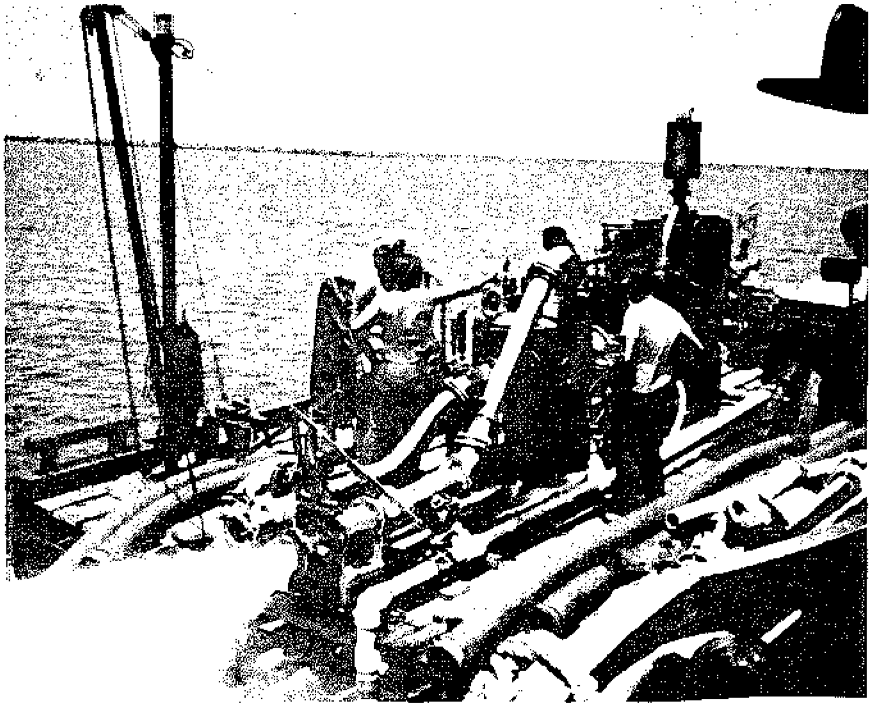


Figure 12. Pump trials at Kawaihae

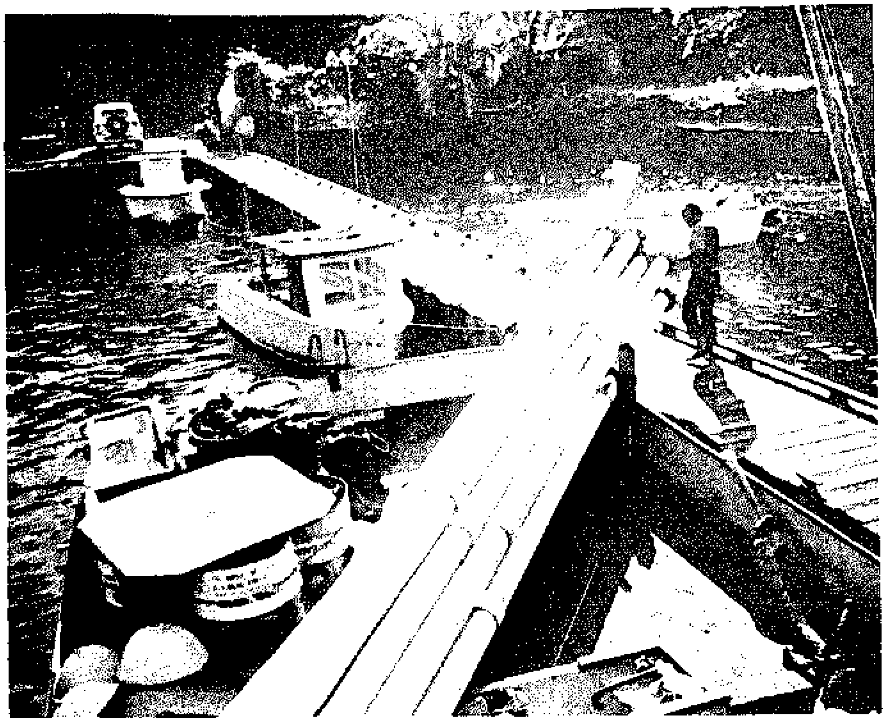


Figure 13. Plastic pipe aboard *Valiant Maid*

The amount of buoyancy provided by these buoys, about 135 lb each, was required to float the pipe while carrying about a 35 percent sand slurry with little wave action or carrying a 25 percent slurry with vertical wave loading from a 6-ft 18-sec design wave. Larger buoys, i.e., those sufficient to support the pipe with a solid sand plug under wave action, were decided against due to the additional bending stresses these would create in the pipe from wave and current forces as well as the additional expense.

The pipe was anchored to the bottom with 1/4-inch cable extending to each side of the pipe at every other buoy station, i.e., every 40 ft. In some places small anchors were used at the cable ends, but in most cases it was found more convenient to loop and shackle the end around a coral head. A section of the sea pipe is shown in Figure 14.

At the foot of the rock shoreline, in 12 ft of water, the sea pipe was connected via a short flexible hose to approximately 50 ft of steel pipe and elbows which ascended the ledge. This juncture was attached to, and held in place by, a 2700-lb clump which had been assembled on the bottom by placing 200-lb concrete blocks in a steel tray. At the top of the ledge, the steel pipe was coupled to the PVC shore piping leading to the discharge area. The pipeline route is shown in Figure 8.

Pipe sections were bolted together underwater with little difficulty when no strain was on the pipeline. Later when the barge was moved and

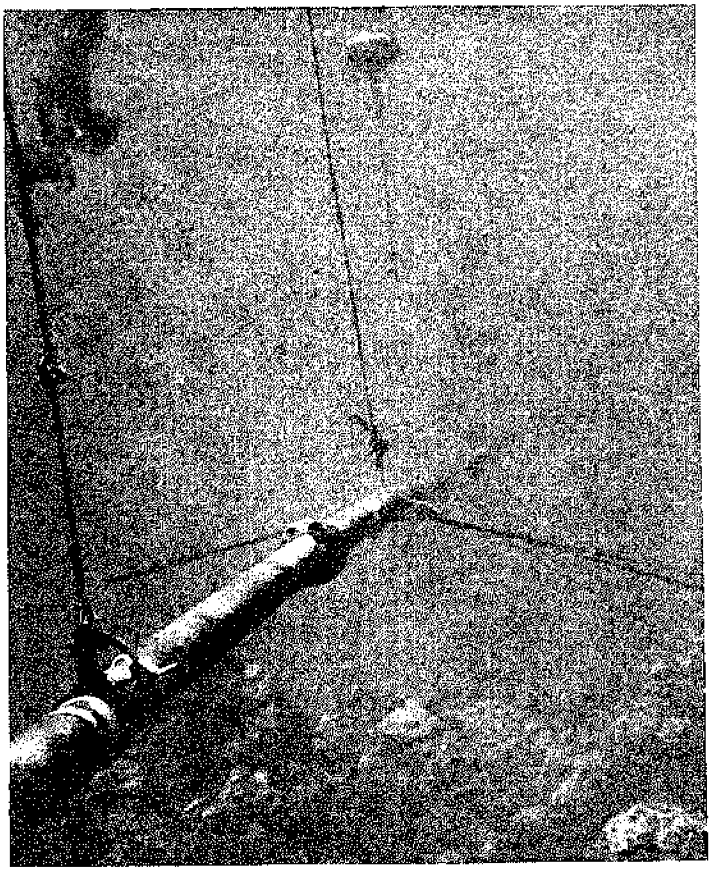


Figure 14. Section of the sea pipe suspended beneath water surface

additional sections had to be inserted, some problems were encountered when divers attempted to bring two sections together to make the hookup. Some type of come-along must be devised in the future to facilitate this procedure.

Contrary to early reservations about the suitability of PVC pipe for this type of job, the pipe proved to be strong and durable and held up remarkably well. There were no structural failures despite occasional heavy seas and the feeling that nothing could survive in the surge that was encountered near the shoreline. Furthermore, there was no wear detectable on the inside of the pipe upon final dismantling; the glue primer was still evident on the inside surfaces near the joints. This was compared with steel nipples used on hose sections which were visibly eroded approximately 1/16 to 1/8 inch deep. One pin hole leak developed at a glued joint in the PVC pipe--apparently caused by insufficient glue. Eventually, sand eroded this opening, requiring that it be patched with underwater epoxy. The successful performance of the plastic pipe was significant, as it would have been difficult to utilize steel pipe without seriously affecting the portability of the SSRS.

Deposition and Settling Basins

A deposition basin 100 ft x 300 ft x 6 ft deep was designed to hold 6000 cu yd of sand. An adjoining settling pond 40 ft wide by 60 ft long by 4 ft deep connected by a weir to the discharge basin was designed with a safety factor of two to remove all suspended solids and allow only clear water to flow back to the sea.

The basins were created in a rough lava field; approximately two weeks were required to complete the work, which included the construction of a short access road, at a total cost of approximately $5,000. Figure 15 shows the deposition basin just after completion.

Figure 15. Deposition basin just after completion

The ability of the coarse lava rubble bottom and walls of the deposition basin to retain the sand slurry was in doubt from the beginning. Consideration was given to lining all or part of the basin with polyethylene sheet or burlap to prevent sand loss by percolation. Since it was felt that the sharp corners of the lava rocks would be likely to punch holes in the poly sheet anyhow and since the cost of burlap was prohibitive, it was decided to leave the basin bare. This decision took a toll in sand, money, and manpower.

When sand pumping began, it was nearly impossible to retain any sand in the basin without continual attendance. The water simply flowed down into the larger voids in the lava carrying the sand with it. The sand could only be retained by creating small ponds within the basin to allow it to settle out and pack into these voids. Much hand shoveling was done in these early days. Finally, when a thousand or so yards were retained, heavy equipment was used to spread the sand over the entire bottom and up the side walls to prevent further significant loss; occasionally, the larger holes would reopen when the layer became too thin. Figure 16 shows the basin after being lined with sand. (Note the barge, pipeline, and *Valiant Maid* in the background.)

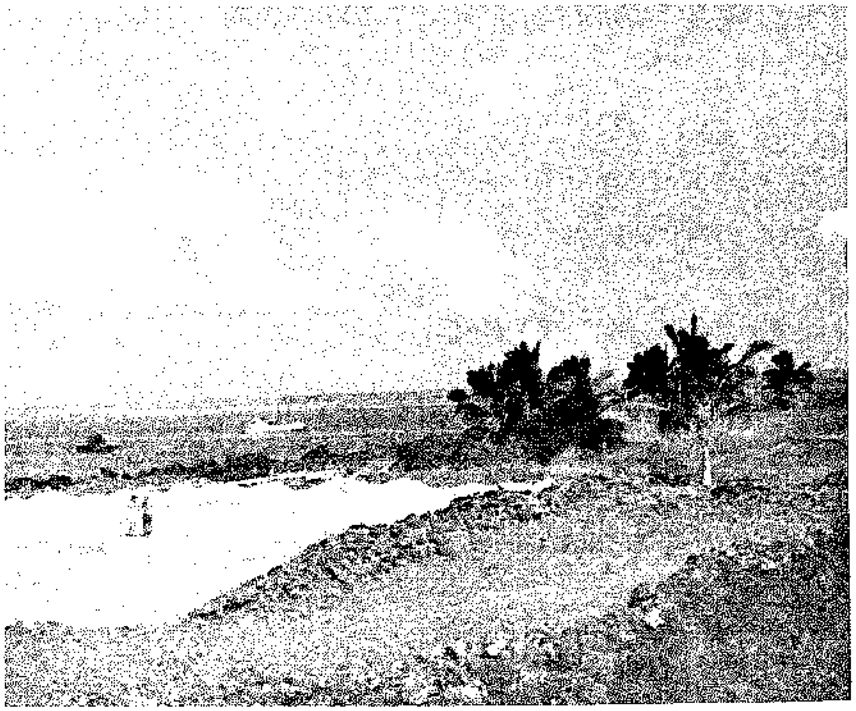


Figure 16. Deposition basin lined with sand

It is estimated that at least 1000 cu yd were lost into the lava. There was no indication from shoreline surveillance that the sand was returning underground to the ocean. It was assumed to have merely been filling the subsurface voids; nevertheless, it was effectively lost from use.

An additional mistake in the design of the deposition area was the assumption that the sand would flow out and fill the basin fairly uniformly. Instead, most of the sand was deposited in the vicinity of the discharge pipe and had to be moved to the remainder of the pit periodically with the use of a front loader or bulldozer. This was difficult while pumping was in progress and was only really possible with any effectiveness when pumping had ceased and the water drained off. Much time and money were expended unnecessarily in handling the sand within the basin.

More efficient design of the basin should have included a means of directing the flow readily to various discharge points along its length, allowing one area to be clear for truck haul-out while another area was receiving the slurry.

Mining

Volume and hours pumped

Sand pumping commenced on September 6, 1974 and continued with many interruptions until November 21. Some pumping was carried out on 44 of the 57 working days. During these 44 days, a total of 253 hours, or an average of about 5-3/4 hours per day, were logged in which sand was actually being pumped ashore.

Failure to pump any sand for 13 full days during the test period was entirely the result of downtime for mechanical repairs. The longest interruption was for ten days while overhauling the 200-hp Continental diesel engine driving the main pump.

On the days in which pumping was carried out, failure to average more hours of pumping was again chiefly the result of mechanical problems but to a lesser extent due to unfamiliarity with the equipment and delays in repositioning the barge. Much longer pumping days were achieved in the latter days of the experiment. No time was lost because of weather or sea conditions.

The exact volume of sand deposited ashore is uncertain, but the figure lies somewhere between 10,500 and 13,600 cu yd. The first figure represents the sum of that which was estimated to remain in the deposition basin at the termination of the test, or 4,000 cu yd, and an estimated 6,500 cu yd which was removed by truck during the operation to a nearby stockpile. The 13,600 cu yd figure is taken from daily logbook entries based on hours pumped and slurry concentration readings. The discrepancy may be attributed to one or more of the following reasons:

1. Possible overestimation of the flow and/or sand content of the slurry
2. Possible underestimation of the amount of sand removed to the stockpile or remaining in the basin
3. Sand lost into voids in the lava foundation of the deposition basin

Based on these minimum and maximum figures the average hourly sand flow rate was between 41.5 and 54 cu yd/hr or an overall estimate of about 48 cu yd/hr.

Downtime

The following major time-consuming problems caused a loss in pumping time:

1. The blowing of head gaskets and radiators, along with other minor difficulties, of old, rundown, surplus diesel engines which powered the pumps--each requiring overhauling in the field.
2. The repeated fracturing of a flex-plate coupling between the main pump and engine--each time requiring several days to repair.
3. The inability of the 6-inch plastic hose (B.F. Goodrich Radial Flex--connecting the manifold to the suction probe and to the discharge pipe) to withstand the strains placed on it by the motions of the barge even though working pressure of the hose was never exceeded. Sections of this were later replaced with another brand believed to be Gen-Line by General Tire and Rubber Co. which held up better. The continual rupture and repair of this first type was indeed frustrating and time-consuming. A rubber, wire core, dredge hose should be considered in the future.
4. Due to age, the repeated bursting of the surplus 3-1/2-inch fire hose used to supply drive water to the jet pump.
5. The wearing through of the housing on the Gold Divers, Inc. 6-inch jet pump after pumping about 5,000 cu yd of sand--requiring disassembly and replacement.
6. The loss of many pipeline buoys due to poor securements to the pipe and due to weak eyes in the buoys. Although this did not necessarily cause downtime, it resulted in excessive pipeline maintenance time.
7. The failing of an o-ring seal on the Char Lynn hydraulic motor driving the crusher--requiring major dismantling to repair.
8. The inability of the first rotary actuator to generate sufficient torque to open and close the sand inlet valve when the suction probe was beneath the sand. Until this was replaced by a new, more powerful one, divers had to make the adjustment manually.
9. The failing of the elbow leading overboard from the manifold to the flexible hose coupled to the discharge pipe on two occasions. The bolts sheared once and, on a second occasion, the elbow fatigued and buckled due to the sometime violent barge motions. A ball joint should probably be utilized at this point.

The suction probe and its effectiveness

All together nine probes were attempted, two of which resulted in very small craters--roughly 100 cu yd. Using an estimated volume of sand recovered of 11,500 cu yd and ignoring the two small craters, the average extraction from each crater can be calculated as 1650 cu yd.

The tests provided a great deal of information concerning the operation of the suction probe and this technique of sand recovery.

Details of various functional aspects of the operation of the suction probe are contained in the following subsections:

Jetting-in. Although the required negative buoyancy for jetting was computed at 40 lb, the probe actually had to be ballasted considerably more than that to accomplish full sand penetration. At the commencement of jetting, 40 lb were sufficient; however, as the probe got deeper into the sand, it began to "float" in the hole. This was probably the result of drag forces on the external surfaces of the probe as the jetting water rushed around it to the surface. Another possible cause may have been the fluidizing of sand by the jetting water, creating a high density soup around the probe resulting in higher buoyant forces. In any case, it was found that the probe should be about 300 lb negative under static conditions in order to perform properly during jetting.

One consequence of this problem was the disruption of the vertical stability of the probe. Reducing the buoyancy by such a large amount resulted in a severe reduction of the righting moment.

Previous tests of the prototype, which were conducted in 1972, had relied on a guide pipe arrangement to keep the probe upright. A small diameter pipe was first jetted into the sand and then the probe was clamped to it with loose fitting sleeves. The probe could then slide along the pipe as it jetted into the sand.

In its present mode, the guide pipe has been eliminated and vertical stability is provided by the moments generated by the separation of the center of buoyancy and center of gravity. With the reduction of this moment, slight currents could tilt the probe while jetting, causing it to enter at an angle. In strong currents, the problem could become serious.

Additional problems were incurred when the fiberglass buoyancy tank attached to the probe was fractured upon striking the side of the *Valiant Maid* during deployment. Under bottom pressures, water was forced into the tank at the fracture, compressing the foam and greatly reducing buoyancy. Repairs were never satisfactory and the situation was only remedied by replacing it with a newly fabricated steel tank.

Despite these difficulties, the probe was able to be jetted in satisfactorily during the tests. Future refinements of the probe which would increase the vertical rigidity are envisioned.

On two occasions the probe apparently struck a large rock or coral head in the sand, impeding its motion. It was simply pulled out and re-jetted nearby. Figure 17 shows the probe jetted into the sand.

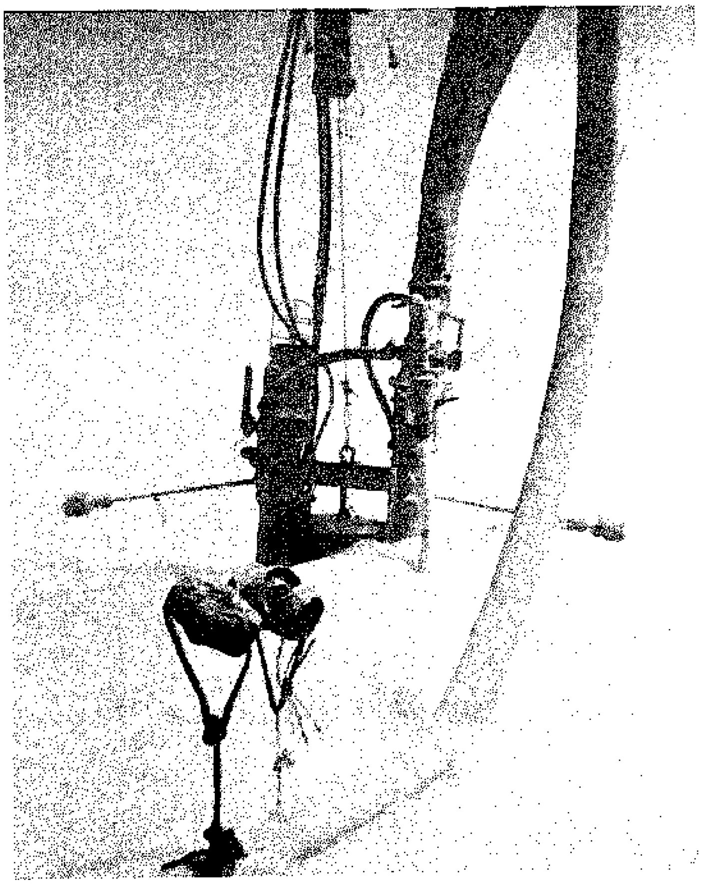


Figure 17. Suction probe jetted into sand

Crater formation. Lab tests with scale models in clean, relatively loose sand always produced craters which were formed by the sand gradually slumping at the center--starting as a small crater with side walls somewhat steeper than 32 degrees and growing larger in diameter as it deepened until the crater apex reached the sand inlet. At this point the crater was nearly fully formed and in only a very short time the side walls reached an angle of repose of about 32 degrees and sand flow ceased.

Earlier, in field tests conducted off Waikiki Beach, somewhat steeper walls were noted initially, but the crater formation proceeded in the same fashion as it did in the lab, especially at the slower pumping rate of the 3-inch model.

In the current tests, crater formation was markedly different most of the time. At the commencement of pumping, after jetting-in, a cylinder of sand roughly 3 ft in diameter, extending down to the sand inlet and corresponding to the sand that was disturbed during jetting, was removed immediately. In the succeeding half hour or so, only very light slurry was achieved--about 5 percent. Water was drawn directly into the sand inlet and only a small supply of sand gradually spilled in from nearly vertical side walls. As time went on and the diameter of the cylinder became greater, the surface area of sand along the walls exposed to the water increased, and the flow of sand toward the sand inlet likewise became greater. Soon, the sand supply exceeded that being removed by the system and loosened sand started to accumulate around the probe. The slurry percentage rose and this loosened sand was removed in the familiar cratering fashion observed in model studies with angles of repose of 32 degrees.

The cause of this type of cratering is obviously due to greater cohesive forces between sand particles than was experienced with underwater sand in the laboratory. Increased cohesion could be the result of the 3 percent silt content of this body of sand or possibly from decayed organic matter in the sand. Furthermore, the age of the deposit may have had some bearing on the apparent cohesive properties of the sand. It is likely that the sand was here for hundreds or thousands of years and was compacted to such a state that much of the pore water had been forced out, creating a damp state. It is known that damp sand has much larger intergranular forces due to surface tension than wet sand, as is commonly understood by anyone who has built a sand castle on the beach. The compacted sand in the deposit would exhibit damp state properties until transposed to a wet state as water penetrated the walls.

This condition was somewhat troublesome in that sand flow was minimal initially, with very little corrective action possible since the system concept depends upon the sand flowing to the head of the probe. Some expediting of the sand flow was effected by a diver probing the side walls with a separate jetting pipe. This was not really very efficient.

In all, this reduction of flow at the outset, of possibly one hour's duration, did not significantly decrease the overall efficiency of the system since one hour was only a small portion of the total pumping time in a crater. Some craters were pumped for 40 hours or more. The phenomenon is worth keeping in mind, however, if larger capacity cratering systems are contemplated. It may be that the natural inflow rate of much submarine sand is not sufficient to warrant the construction of a system larger than the 6-inch system tested here.

Fluidizing pipe. As is shown in Table 1, the maximum volume of sand recoverable from a 20-ft deep crater is about 800 cu yd. In order to increase that take, a fluidizing pipe was tried and found effective. The idea was suggested by Inman and Harris (1970) in their paper "Crater sink sand transfer system."

A 1-1/2-inch PVC pipe with 1/4-inch holes drilled every 6 inches was laid, with the holes facing downward, from the apex of the crater up along the wall. The lower end was coupled by flexible hose to the high pressure water being used to drive the jet pump; the other end was capped. As the water jetted out of the holes, the pipe buried itself in the sand. The fluidized sand created by the jets flowed, as any fluid, by gravity down to the center of the crater and was sucked into the system. The trench formed by the pipe initially had vertical walls as described earlier, but gradually these would cave-in, creating tremendous rushing of sand and water toward the center. (See Figure 18.) The flow, similar in nature to a turbidity current, was so strong at times that a diver could not maintain his position in it.

Figure 18. The fluidizing pipe removing sand

This fluidizing pipe greatly improved the volume of sand removed from each crater. In essence, it created a new crater emanating from the tip of the pipe, in turn, feeding the original crater. The perimeter of this crater would sometimes be 20 ft or more beyond the tip of the pipe (Figure 19). The pipe was rotated periodically about the probe along the crater wall. The resulting crater had a rosette appearance when pumping was concluded.

The largest crater formed by this method (probe station 5) was 20 ft deep and measured about 150 ft across at some points. Eleven days were spent pumping this crater alone which is estimated to have yielded 4700 cu yd of sand. The reason for the success of this crater is that a penetration to about 24 ft was achieved near the center of the deposit, placing the sand inlet at about 22 ft beneath the surface. Elsewhere, penetrations were to less than 20 ft.

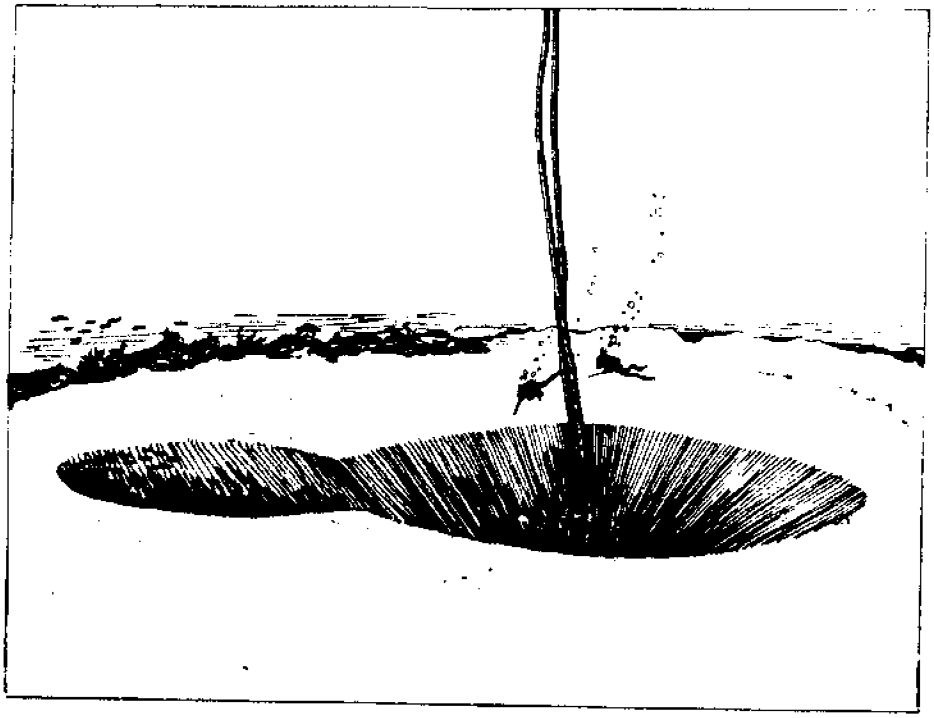


Figure 19. Crater formation with fluidizing pipe

The fluidizing pipe was not without problems. The major difficulty was controlling its rate and extent of burial. When allowed to bury freely, it would proceed to bury itself to a horizontal position or until it hung up on rocks or coral in the sand.

The fluidized sand would flow until some angle above the horizontal is reached and then cease, leaving the fluidizer buried and difficult to retrieve even with the supply water still on.

Attempts were made to tie off the end of the pipe by some means to restrict its downward penetration. These attempts were futile as it was difficult to find anything to secure the pipe to that wouldn't eventually tumble into the crater itself. It was also difficult to determine the extent to which one wanted to let it be buried. If securement were made and if the pipe were allowed to burrow in steps, rocks would collect under the pipe, making succeeding steps impossible without clearing the rocks.

Another difficulty caused by the fluidizer was that, if the probe were buried to say 20 ft, it would be possible to bring sand in at such a rate that it would pile up around the probe and bury it completely, covering the water intake. This never happened, but it came within inches. Such an occurrence would be likely to cause a complete plug in suction and possibly discharge lines.

Slurry control. A supposition in the design of the system was that the sand/water mixture could be kept constant if the sand/water inlet size ratio were kept constant. The ratio needed to produce a 20 percent mixture by volume was determined empirically from the model studies. A 4-1/2-inch square sand inlet opening was required with a 6-inch water intake to the mixing box.

The tests revealed that the different states in which sand can exist underwater have a large effect on the slurry percentage that will be obtained. As mentioned earlier, when the sand is compacted or likened to a damp state, flow is slow and would be effectively nil if it were not penetrated and loosened by the water. In the wet, loose state it flows easily, stands on a 32 degree angle of repose, and is identical to the underwater sand observed in the laboratory flume. In this state, a slurry of about 20 percent was realized during the experiment. Finally, in the fluidized state, sand acts as a dense liquid and flows much more readily than in other states.

During these tests, fluidized sand caused the sand percentage to rise to 40 percent or more and caused cavitation to occur in the pump. The jet pump generally prevented complete overloading and loss of suction, yet prolonged operation at such a high percentage was undesirable. Fortunately, an easy remedy was available with the SSRS. Within seconds, the sand inlet could be partially closed hydraulically to restore the sand percentage to the desired figure. The only drawback here was that the full sand inlet opening was desired over the long run in order to pass material produced by the crusher.

Attempts at modifying the internal plan of the mixing box to reduce sand flow were not successful. Later, a bypass was added from the jet pump drive water to the intake tube. By increasing the speed of the 4-inch pump during times of heavy fluidization, one could slightly pressurize the intake tube while adding more water at the jet pump, thus reducing the slurry percentage.

Fluidizing was not only caused by the fluidizing pipe, but also resulted from the precipitous crater walls. Vertical walls 8 ft high would send sand cascading down into the crater like a waterfall. (See Figure 20.) The sand would boil up at the bottom and flow down to the crater center in a suspended or fluidized state. What collected around the head stayed in suspension for quite some time in a dense, soupy consistency. Divers would sink into it like quicksand.

Thus the problem of maintaining a constant and optimum slurry percentage was not as easy as first supposed. Yet, with the methods developed, a slurry as high as 35 percent could be maintained during fluidization. An overall average of about 20 percent was sustained throughout the testing period.

An additional problem affecting the slurry was due to blockage of the sand inlet by foreign matter--coral, shells, rocks--causing sand production to fall off to zero occasionally. When it was determined by a diver that this was not caused by a lack of sand around the probe, it was assumed that some blockage was occurring--even though this condition could never be observed.

Figure 20. Initial vertical walls of crater

The problem could have been caused by particles either bridging the square sand inlet after passing through the crusher or collecting outside the crusher. It is likely that both effects occurred.

Long, thin pieces of finger coral or auger shells were shaped so they could pass through the crusher rollers and lie across the 4-1/2-inch sand inlet--eventually causing a jam-up. Backflushing could usually clear up such a problem unless such fragments were excessive as was experienced near the edges of the deposit.

Very large pieces which were too large to be grabbed in one bite by the crusher could rest outside against the rollers. These were usually worn away by reversing roller direction to get new bites. On one occasion the probe was removed and re-jetted to get away from such a piece.

Lastly, by feeling down the probe to the crusher mouth, it seemed as though jam-ups were occurring between the crusher housing and the hard packed sand just adjacent to it. A bridge of debris would form above the crusher, eventually cutting off much of the sand supply. It would generally collapse of its own accord or be removed by backflushing, both of which could be noted by the sudden clamor of rocks through the pump.

Miscellaneous notes

Pump clogging. The crusher was designed to produce particles no larger than 2 inches thick x 2 inches wide x 4-1/2 inches long. The port width of the impeller on the Amsco Wearmaster pump used was 3-5/8 inches. The manufacturer advised that occasional pieces of the size described would probably cause no problem for the pump, yet recommended that a cleanout or screening be used to hold particle size to below 2-1/2 inches.

A cleanout plate ahead of the pump was installed and was used frequently. On an average of three or four times per day, the impeller would jam-up with rocks and coral causing a loss of suction and impeller unbalance. About 25 minutes were required to shut down the system and remove the rocks.

Flow rates. Water flow rates through the 4 and 6-inch lines were measured using an Ellison "Annubar"--a device which measures the differential between stagnation and stream pressures. This, however, could not be accomplished while pumping sand because of clogging and damage which would occur to the sensor. Devices capable of measuring slurry flow were beyond the financial means of the project.

The flow rates while pumping sand were estimated from the clear water rates and by occasionally measuring the height and distance of throw at the discharge. An attempt was made to maintain the 6-inch flow rate at between 900 and 1100 gpm, depending on the percentage of sand being pumped and the distance offshore. However, the flow rate may have dropped to below 900 gpm during heavy loads.

It was intended to supply 300 gpm to the jet pump at 100 psi; however, due to underpowering and engine overheating problems, the best that could be maintained was 300 gpm at 60 to 70 psi. Because of this and higher slurry percentages than had been anticipated, vacuum on the main pump was always in the range of 20 to 22 inches of Hg or just below cavitation.

No precise means was available for measuring the percentage of solids in the flow--again, because of budgetary limitations. Every 15 minutes, a sample of the slurry was drawn off into a graduated cylinder near the discharge side of the pump. After the mixture settled, a reading was obtained. Since the flow near the pump was still turbulent and not stratified, it is believed these samples were valid. Good duplication was achieved. As a check, this was occasionally carried out at the end of the discharge pipe. The samples taken here varied considerably from the top to the bottom in the flow and could not be relied on unless an average was taken. Figure 21 shows the discharge when pumping a fairly high percentage of sand; the basin is nearly full.

Depending on the degree of fluidization, sand percentages generally varied between 15 and 30 percent. Readings above 35 percent would require an adjustment of the sand inlet openings to prevent cavitation as well as sinking of the pipeline. Readings below 15 percent generally was a sign of loss of sand supply due to one of the conditions mentioned under slurry

Figure 21. Sand discharging into basin

control. In this case action such as backflushing or moving of the fluidizing pipe would be taken to restore flow.

Discharge pipe plug. One major reason for desiring a constant or controllable slurry was to ensure that pipeline plugs due to excessive solids would not occur because the task of unbolting and unplugging the pipe would have taken days. Fortunately, throughout the tests, no danger of such a plug was ever eminent as the sand flow could always be shut off in roughly 3 seconds and clear water pumped through the system. Should this have failed, there remained the backup option of switching pump suction to the sea through the manifold and likewise flushing the discharge pipe. If the engine driving the main pump failed, a third option existed. The 4-inch pump discharge could be diverted into the 6-inch discharge line--again, flushing the line. A view of the discharge pipe as seen from the barge is shown in Figure 22.

On the final day of the experiment, discharge pressure suddenly began to rise and the pipeline gradually settled out of sight. All of the flushing options were exercised, but the pipeline stayed down--much to the crew's bewilderment. After several agonizing minutes, the pipe began to clear and slowly rose to the surface.

Upon breakdown of the pipeline, the villain was discovered to be a long, thin auger shell that had squeezed by the crusher and the pump impeller. It was slightly larger than 6 inches in length and had jammed

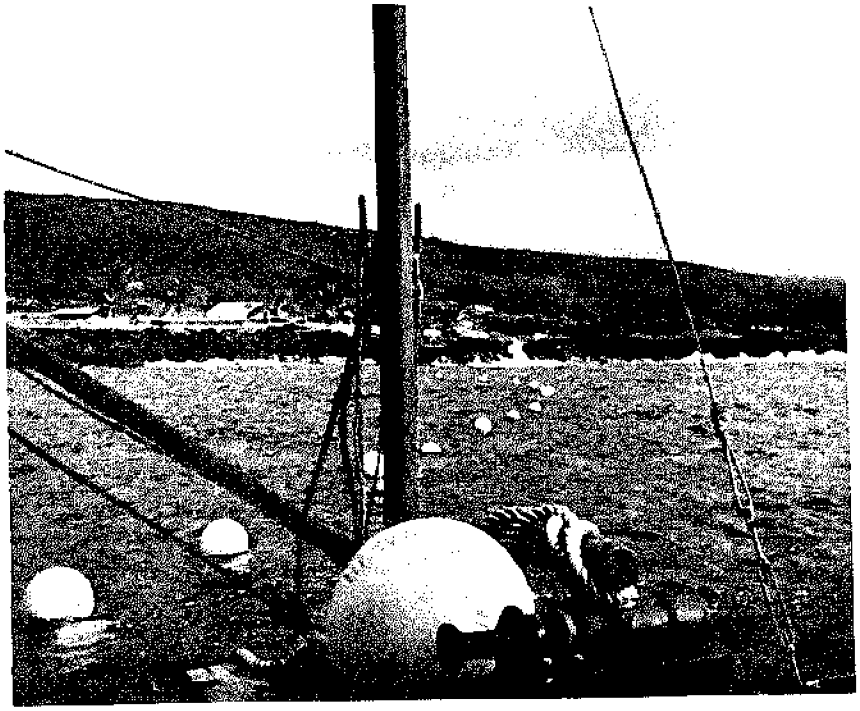


Figure 22. View of discharge pipeline from barge

crosswise against the lip of a nipple in the flexible hose at the shoreline. Rocks jamming behind it caused the plug and only the rupturing of the hose cleared the plug and saved the day.

Depth and distance pumped. Excavation began in 50 ft of water and proceeded out to 65 ft of water. The maximum depth beneath the sand from which removal occurred was estimated at 22 ft and about 20 ft at the 65-ft water depth. Thus, sand was recovered from a maximum surface to a bottom distance of 85 ft. An increase in the jet pump pressure and flow would probably be needed beyond this depth.

In all, the maximum length of pipeline deployed was 1420 ft with a static discharge head (vertical rise from sea level) of 20 ft.

RESULTS AND CONCLUSIONS

The objective of this field experiment was to transfer a sufficient quantity of sand from the ocean bottom to a shore site using the SSRS such that a first assessment could be made of the technical, economic, and environmental feasibility of future beach nourishment or other commercial operations using this system. From this standpoint the tests were very successful.

Technical Aspects

The SSRS satisfied the design criteria and can be considered a technically feasible system.

Crew requirement

The SSRS was designed for operation from a small vessel with a small crew. Four men operating in two-man shifts were sufficient to run the operation. The crew members consisted of the project leader, two graduate students, and the skipper of the *Valiant Maid*--none of which were experienced in dredging. A certain overlap of the shifts was required each day for the purpose of refueling, maintaining the pipeline, and moving the suction probe and barge when required.

When the probe was emplanted in a productive sand area, one man was actually sufficient to place the system in operation and keep it running. This was done on occasion to test the feasibility of a one-man crew. Although it proved possible, a second crewman is normally desirable for safety purposes, especially when diving is required. Figure 23 shows a crewman on watch. His duties consisted chiefly of monitoring pump pressures and slurry densities and adjusting the sand inlet valve as necessary.

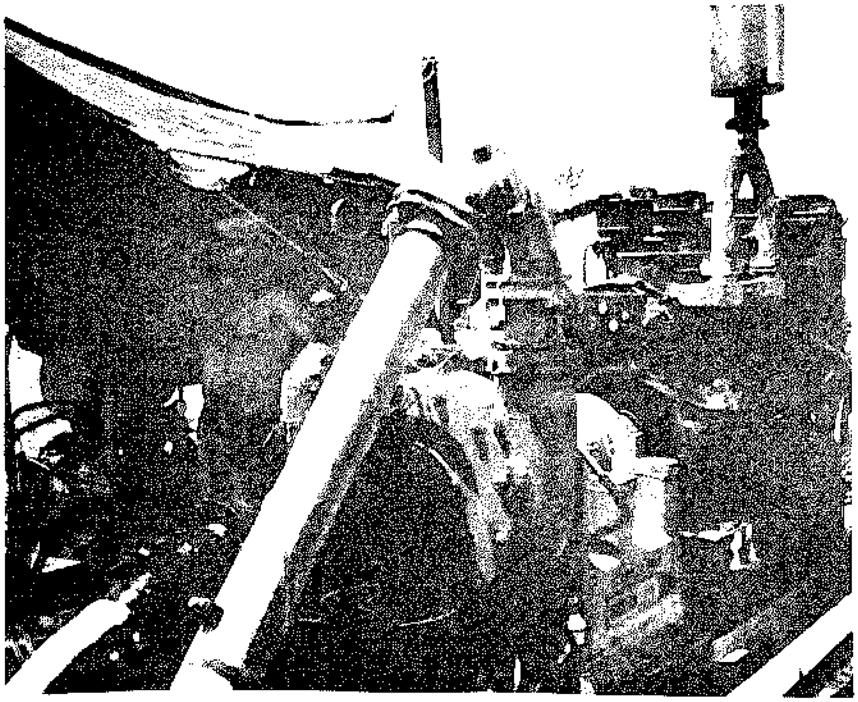


Figure 23. Graduate student on watch monitoring pump pressures and slurry densities and adjusting the sand inlet valve as necessary

Production

The design sought to maintain an average production rate of 50 cu yd/hr over a 10-hour day. This average rate was maintained although rates as high as 75 cu yd/hr were achieved occasionally. Ten-hour pumping days were possible, but were not the rule, mainly because of engine and equipment failures.

Although it was technically possible to recover up to 30,000 cu yd of sand over the 3 months allowed for testing, only a little more than one third of that figure was recovered. This again is attributable to machinery breakdowns and the extra time spent in learning. It is estimated that this same system could easily achieve a 10,000 cu yd/month production rate simply with better support equipment.

Sea state capability

The pumping operations took place during the early winter sea conditions. Surf of up to 12 ft broke onshore on several occasions and battered the nearby Kona Surf Hotel, closing a portion of the poolside bar some 25 to 30 ft above sea level. Pumping was never interrupted by these seas which were 5 to 6 ft at the barge site. Fortunately, the pipeline exited the water at a small indent in the coastline which was deep enough and aligned in such a way that the pipe was not subjected to severe breakers, but rather to a strong surge.

Effects of the swell did cause the flexible hose going over the side of the barge to split and an elbow to buckle, but these problems can be easily prevented in the future.

Suction probe concept

The concept of a semi-fixed, buried suction head combined with a crusher was effective in the Hawaiian marine environment where coral becomes a consideration both from an ecological as well as a technical viewpoint. The living coral nearby must be protected from damage and the dead coral in the sand must be reckoned with at the sand inlet. The crusher worked exceptionally well and was able to pulverize even the hard basaltic rocks found in this deposit; however, the crusher may well be dispensed with in a temperate climate where the sand is likely to have less impurities. The suction probe experienced some difficulties in jetting and stability as mentioned earlier, but these can be readily overcome. In all, the probe was easy to handle and provided a means of uncoupling a suction head from the surface motions of the support vessel while maintaining effective control over the slurry percentage.

It is evident that the SSRS is only suited to thick sand deposits even though considerable benefits can be derived through the use of a fluidizing pipe in thinner sand areas. It is recommended that the method be considered only for deposits which are 20 ft or thicker.

Depth capability

A late objective in the design (due to new legal requirements in Hawaii) was to permit operation in fairly deep water without the need for divers. This has not been accomplished at this point. Divers are still necessary for certain operations--such as jetting in and retrieving the probe and when the fluidizing pipe is used. They are also used for inspection as when the slurry percentage falls.

Depth limits imposed by lift requirements were nearly reached during the experiment with the jet pump supply water utilized. It is estimated that recovery could have continued to a maximum of 100 ft with this equipment without a significant loss of flow. Deeper mining would require a larger drive pump for the jet pump. An alternate means of going deeper would be through the use of an air lift, which would be most practical if retention of the sand in a barge on the surface were contemplated.

Environmental Aspects

Although a thorough environmental report will be forthcoming, a brief summary of which appears as Appendix A, some mention here of the immediately observed effects follows.

Turbidity and sedimentation

The suction probe caused a greater amount of turbidity than had been expected (Figure 24). This was primarily a result of the way in which the sand collapsed into the crater. As mentioned, the precipitous side walls of the crater poured sand in from as high as 8 ft. The resulting turbulence released silt into the water which generally remained within the crater. The fluidizing pipe aggravated the problem as the rush of sand and water from one direction into the center of the crater seemed to cause an upwelling at the probe with a component in the direction opposite from the fluidizer; that is, silt was carried up and away from the fluidizer direction. The resulting cloud extended 100 ft or more from the probe, depending to some extent on the velocity and direction of the ambient current. Figure 25 shows some turbidity caused by the cratering.

There was no direct runoff from the discharge area to the sea. Water return was by percolation through the lava rock. There was no apparent turbidity caused by the return flow.

Anchor damage

The most apparent damage to the adjacent coral communities was caused by the barge anchors and cables. As the barge rode on its moorings, or when it was repositioned, anchor cables would chafe on the very delicate finger coral, *Porites compressa*, and cut away large swaths. In addition the 360 degree swinging of the *Valiant Maid* would similarly lay flat areas of this coral. A better designed mooring system could eliminate this problem in the future.

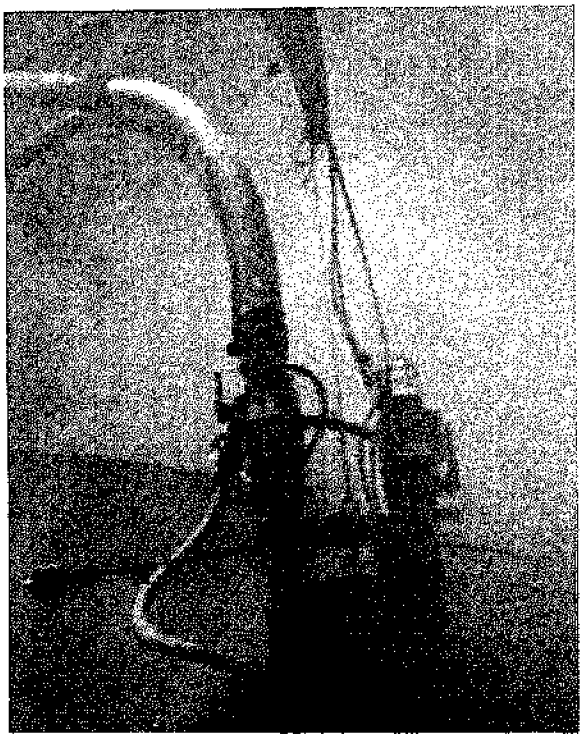


Figure 24. Turbidity caused by probe

Figure 25. Goatfish (weke) feeding in water

Weke rearing

One species of Hawaiian goatfish, the weke, appeared to thrive on the organisms uncovered by the mining. Beginning with a half dozen or so small weke and growing to a large, apparently conditioned school of over a hundred, these fish were on the scene daily, feeding voraciously in the crater. Although mainly feeding on small organisms, they seemed to enjoy the large lugworms which were abundant in the upper layers of the sand.

Interestingly, since they could only feed while cratering was taking place, they would trail behind a diver looking for the first signs of sand pumping. Some of the fish grew to 18 inches in length and weighed several pounds. Since their presence was curious and entertaining, the fish were never harvested. Figure 25 shows weke feeding during pumping while Figure 26 shows the fish circling around just after jetting-in.

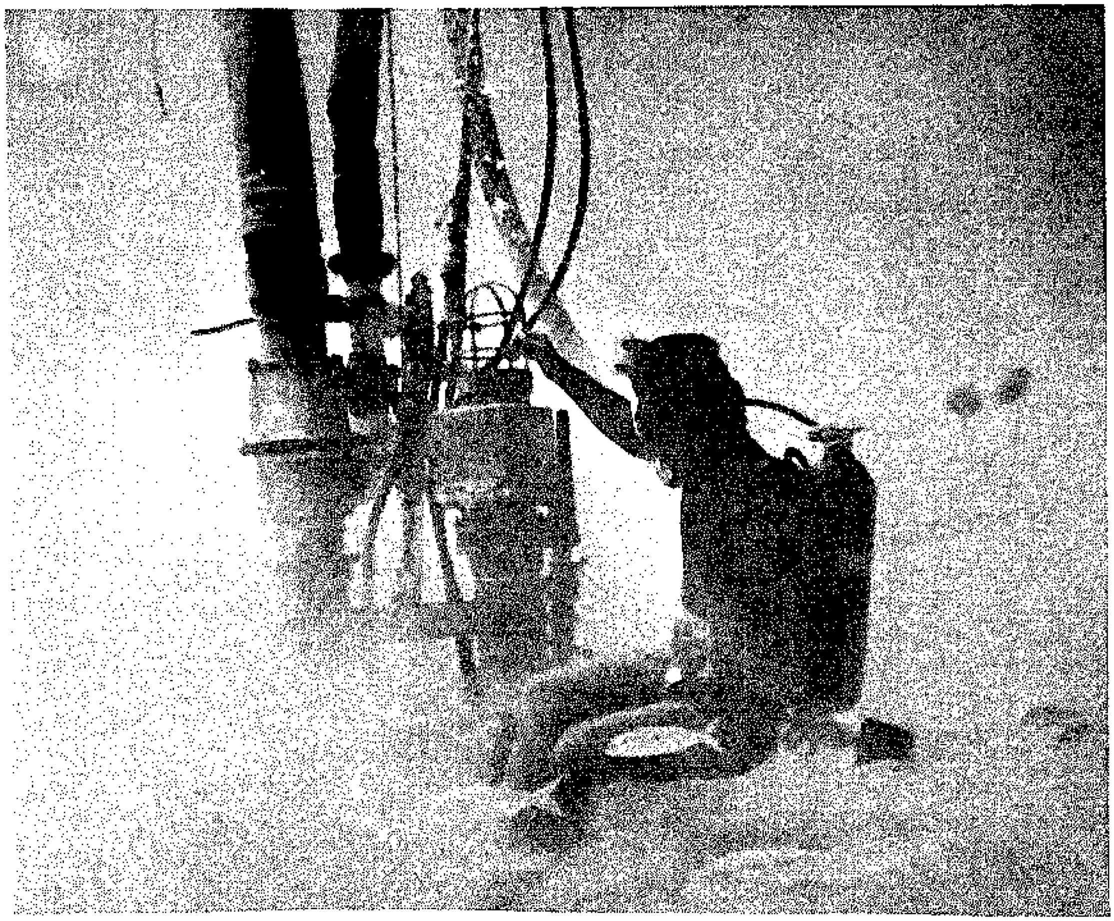


Figure 26. Goatfish circling probe after jetting

Refilling of the craters

Upon termination of the experiment, a bathymetric survey was conducted by divers using depth gauges and measuring lines. A similar survey was conducted exactly four months later. Because of the extreme unevenness of the bottom, as can be been in Figure 27, these surveys are only approximately represented in Figures 28 and 29. They are sufficient to show that the craters were filled in by anywhere from 2 to 4 ft over that period. It was reported that no extremely high surf had been experienced during that time, although some moderately high waves had occurred.

In general, after four months, the craters were rounded at the lips and flattened in the center. The craters appeared to trap fine material as the bottoms seemed to contain a higher percentage of silt than the remainder of the deposit.

Figure 27. Uneven bottom after mining

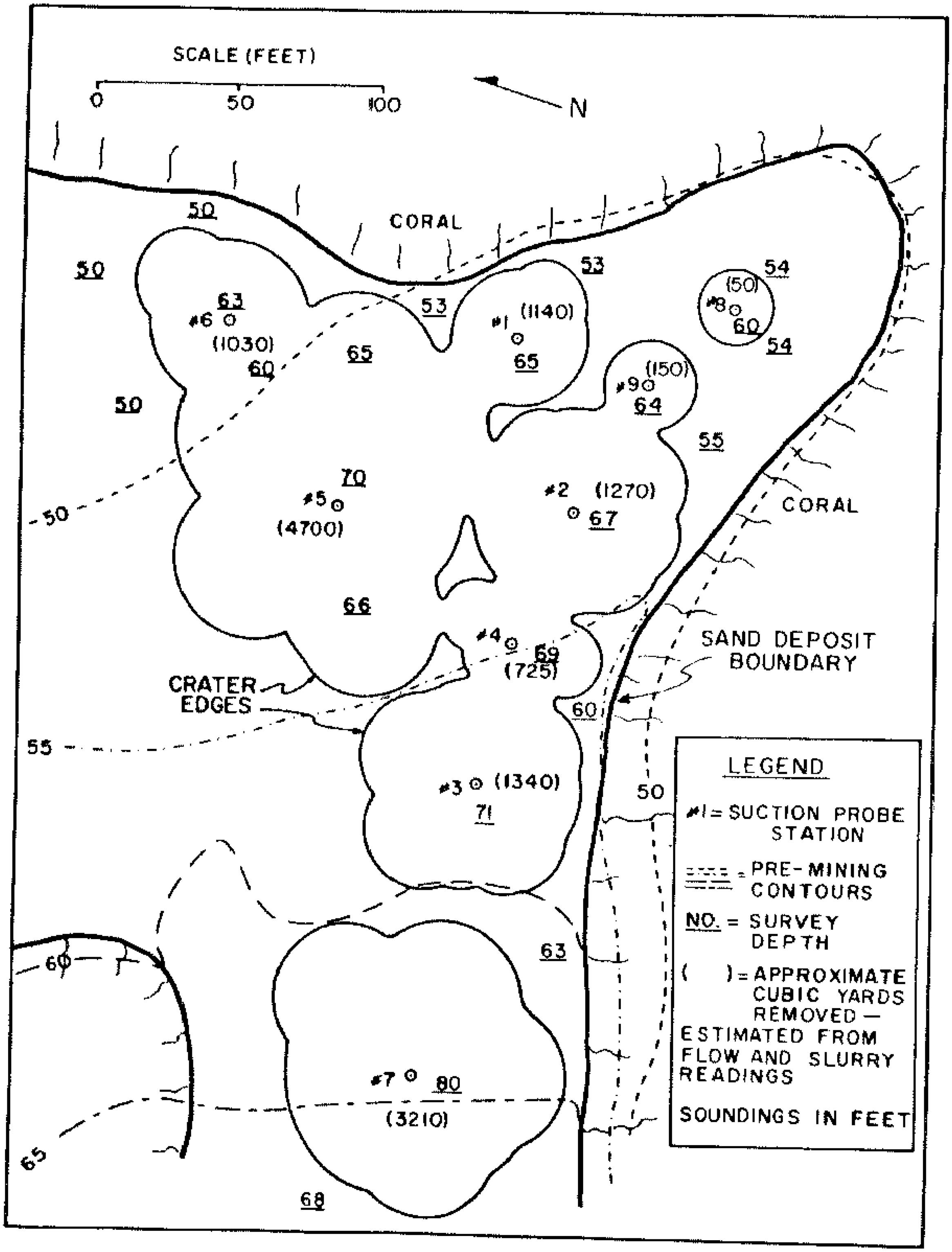


Figure 28. Bathymetric survey immediately after mining

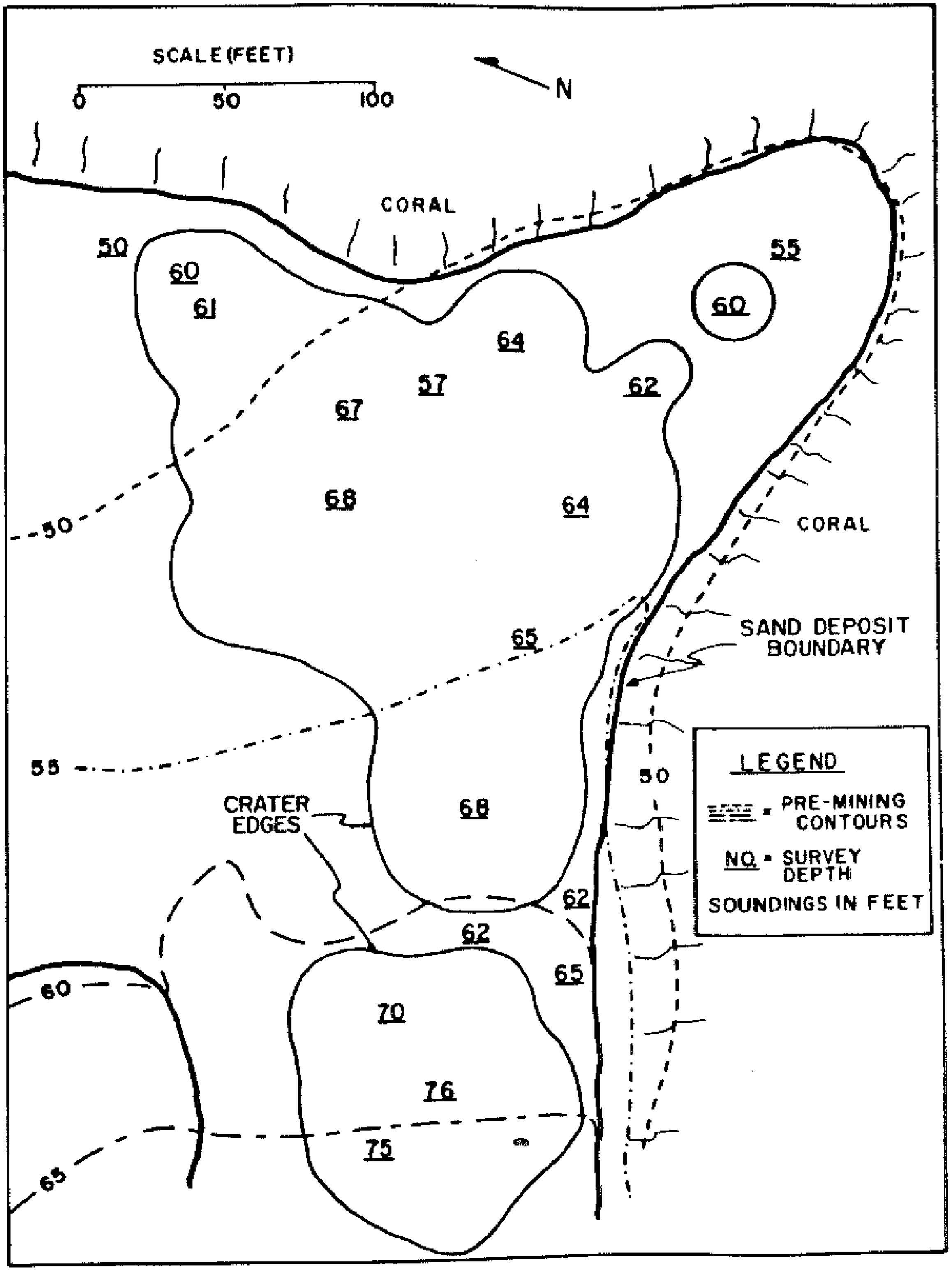


Figure 29. Bathymetric survey four months after mining (March 30, 1975)

Economic Aspects

Appendix B is an economic analysis of sand recovery with the SSRS performed by Dr. Jack Davidson with information supplied by the author. Results for two sizes of operation--10,000 cu yd and 100,000 cu yd--show projected per yard costs at roughly \$5.50 and \$3.00, respectively. This may seem high when compared with conventional dredging costs that are reported as low as \$0.50 to \$1.50 per yard elsewhere, yet is is low when contrasted with sand costs in Hawaii which can be as high as \$30 per yard on the Big Island.

As is shown in this analysis, volume is an important factor in the unit costs of a dredging or mining operation. Operations larger than 100,000 cu yd could be carried out by a large conventional dredge at a lower per yard cost than would be possible using the SSRS and in a much shorter time. However, for small jobs, mobilization costs would probably make it impractical and uneconomical to use such a dredge. This is especially true in Hawaii where an oceangoing dredge would have to be brought in from the mainland or the western Pacific.

Environmental effects and sea state capability are other factors which would bear on a comparison between the SSRS and other systems.

A large initial cost which favors larger operations is the preparation of environmental impact statements. The cost of an EIS will be approximately the same regardless of the project size. Policy in Hawaii, concerning when and under what conditions an EIS is required, will determine if small operations can be feasible in the future. An EIS requirement for an operation of 10,000 cu yd or less will more than likely make such a job impractical.

ACKNOWLEDGMENTS

This project was sponsored by the Sea Grant Program which provided the major source of funding for the work leading up to the tests. The understanding and support of University of Hawaii Sea Grant Director, Dr. Jack Davidson, were of great importance and are much appreciated.

The experiment could not have taken place without the personal cooperation and assistance of Mr. Guido Giacommetti, President of Kamehameha Development Corporation (KDC), and Dr. John Craven, Hawaii Marine Affairs Coordinator (MAC), and their respective staffs, especially Frank Corkran, resident engineer for KDC at Keauhou-Kona and Howard Pennington of the MAC office. Furthermore, the matching funds provided by these organizations through the Research Corporation of the University of Hawaii constituted the sole source of funds for the actual field work.

The operation itself owed its success to the loyal and competent performance in the field of graduate students Steve Nicinski and Jim Vansant and Ed Bilderback, skipper of the *Valiant Maid*, whose know-how and tenacity kept the operation alive in its worst moments.

In addition, the assistance of technicians Henry Ho and Shep Williams in setting up the machinery and pipeline is greatly appreciated as well as that of graduate student, Bob Rocheleau, who helped with the initial surveys, pipeline design, and environmental impact statement.

Thanks also is extended to the rest of the staff of Look Laboratory of Oceanographic Engineering and its Director, John T. O'Brien, for assistance in fabricating and assembling the system and for maintaining the flow of parts and supplies needed on the Big Island. Special thanks to Doreen Brom of Look Lab and Cora Chai of the Research Corporation for administrative and clerical help.

Furthermore, I wish to thank Mr. Robert Q. Palmer, principal investigator of the "Sand Recovery" project from 1968 to 1971, for his help, guidance, and inspiration. I would also like to recognize the following persons for their early contributions in fabricating and testing: Bill Allen, Scott Sullivan, Ed Williams, Keith Nishioka, Leonard Gollob, and Bob Wong.

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APPENDICES

Appendix A. Summary of Environmental Impact Survey

by James E. Maragos (ed.)

Introduction

This summary on the environmental feasibility of the SSRS is based on field studies before, during, and after testing of the system. The field environmental monitoring program was divided among five component studies, each of which concentrated on certain environmental parameters. The detailed analysis of the results of the component studies will be published in a separate University of Hawaii Sea Grant College Program technical report.

The need for the environmental monitoring program was expressed during the processing of permits and the preparation and review of the environmental impact statement (NOAA, 1974) for the SSRS field test at Keauhou.

Environmental study methods

The environmental monitoring program was divided among 5 component studies, each of which was responsible for assessing specific environmental parameters: (1) corals, echinoderms, and water quality--Maragos; (2) sand dwelling mollusks--Hemmes, Macneil, and Ells; (3) fishes--Bowers; (4) sediments and beach profiles--Roach; and (5) benthic algae--Self. A summary of the individual observations and experiments performed before, during, and after the field test is presented in Table A1.

Studies on algae were designed to assess the impact of possible leaching and runoff of slurry from the deposition and settling basins on tidal and subtidal benthic algal populations. The rates of colonization by benthic algae on pipes and other SSRS structures were also noted.

Water quality measurements were taken on oxygen, nutrients, and turbidity to determine whether sand removal promoted the liberation or utilization of these substances.

Prior studies conducted for the preparation of the EIS for the SSRS test at Keauhou (NOAA, 1974) indicated that corals covered nearly 90 percent of the reef surfaces surrounding the test deposit. Coral observations and surveys conducted before, during, and after the test were designed to assess coral responses to possible turbidity generation and undermining of the reef framework due to the removal of supporting sand by pumping operations.

Similar studies were also conducted on the echinoderms, particularly to assess the reaction of sea urchins to the possible increases in turbidity. Other observations on sea urchins were made to determine the impact of the craters on those migrating across the deposit. Occasional observations were also made on marine worms inhabiting the sand and uncovered during sand removal operations.

It was suspected that sand dwelling mollusks were among the most common of the invertebrates inhabiting the sand deposits. Studies were designed to

TABLE A1. SYNOPSIS OF THE ENVIRONMENTAL MONITORING PROGRAM CONDUCTED IN CONJUNCTION WITH THE FIELD TESTING OF THE SSRS AT KEAUHOU-KONA, HAWAII

Description	Field Testing		
	Before	During	After
ALGAE			
Colonization on pipes and other surfaces		X	X
Quadrat surveys offshore from basin and control site	X		X
Quadrat surveys at sand deposit	X		
WATER QUALITY			
Sediment trap experiments at deposit and control site	X	X	X
Turbidity observations and photographs	X	X	X
O_2, NO_2, NO_3, PO_4, and turbidity measurements at deposit and control station	X	X	X
Currents and visibility observations	X	X	X
CORALS			
Reconnaissance of perimeter of deposit and control sites	X	X	X
Permanent transect surveys at deposit and control sites	X	X	X
Observations on responses to turbidity generation		X	X
Observations on effects of collapse and slumping of reef rock towards crater			X
ECHINODERMS AND WORMS			
Quadrat surveys at deposit and control sites (urchins)	X	X	X
Observations of sea urchins in craters			X
Observations of sand dwelling worms		X	
MOLLUSKS			
Collections and censuses at discharge pipe		X	
Night dive observations	X		X
FISHES			
Censuses along permanent transects at deposit and control sites	X	X	X
Observations at craters and along pipes	X	X	X
SEDIMENTS AND BEACHES			
Beach profiles and reconnaissance swims	X		X
Bathymetric stake surveys	X	X	X
Observations along reef rim and in craters	X	X	X

acquire accurate estimates of the diversity and abundance of mollusks at the deposit. These studies provided the estimates on the extent of the destruction of mollusks by sand recovery operations.

The fish surveys were designed to assess whether fish populations would be attracted to or avoid the SSRS operations. Other observations were made on the feeding behavior of fishes in the craters and along the pipes.

The nearest beaches were profiled before and after testing to verify that sand recovery operations did not result in the erosion of the beaches. In addition, reconnaissance swims were conducted between the beaches and the sand deposit to determine whether there were sand channels and other connections present.

Surveys of bottom sediments at the test deposit were designed to determine the extent of sand migration in and out of the deposit before, during, and after the SSRS test. Observations on the formation of the craters, the resuspension of sediments, and the migration of sand away from the deposit boundary towards the craters were also made.

The use of control surveys and replicate sampling enabled objective statistical evaluation of the results. Replicates were taken so that the variation within samples and the precision and accuracy of the various methods could be ascertained. Control station studies were conducted about 1 km north of the test site at another deposit of similar depth, dimension, and distance from shore so that data variations attributed to natural processes could be differentiated from those caused by SSRS operations. Finally, the conducting of studies before, during, and after the field test allowed a documentation of the changes in environmental conditions with time.

Results

The various turbidity studies confirmed that the generation of turbidity by the SSRS was small and confined to the location of the crater being excavated. On only one occasion was a layer of turbid water seen to migrate beyond the boundaries of the crater to the coral reef communities nearby. However, the turbidity particles were so small that they did not appear to settle on the corals and the latter displayed no adverse responses to the turbidity based on subsequent observations. The turbidity was caused by the resuspension of fine sediments during the slumping and cascading of sediments down the walls of the crater during suction head and fluidizing pipe operations. At times the momentum of "turbidity" currents rushing down the walls of the crater and impinging upon the bottom would result in the formation of a turbidity column directly over the crater. Additional turbidity may have been generated by divers swimming along the bottom and dispersal may have been promoted by the rafting of turbid water on ascending air bubbles from scuba divers. The density of the turbidity was never excessive enough to prevent partial visibility through the plumes. Therefore, it is concluded that SSRS-generated turbidity did not pose a significant adverse effect to the marine environment.

The volume of slurry piped to the deposition basin was never sufficient to result in an overflow to the settling basin and ocean. The porosity of the basaltic rock which formed the walls and floor of the basins facilitated rapid percolation and effective filtration of water from the sand. These observations were supported by the shoreline algal studies which did not indicate any consistent or significant effect of the slurry water on the abundance and diversity of littoral benthic algal populations. Slurry water was never detected entering the ocean from the shoreline.

Despite the fact that the water quality measurements lacked the precision and reliability desired, the results provided no evidence of the generation of nutrients and the consumption of oxygen attributed to the removal of sediment from the deposit.

Beach profile surveys indicated that the beaches either accreted sand or did not change their volume after testing of the SSRS. Furthermore, the nearest beaches were located at least a mile from the deposit and reconnaissance swims indicated that the beaches and the deposit were separated by vast expanses of flourishing coral communities over which the transport of sand could not have occurred without leaving noticeable effects. Therefore, it is concluded that the SSRS test did not affect the beaches.

The stake surveys at the deposit also indicated that sand did not migrate in or out of the deposit during the SSRS test except that which was pumped ashore. The elevated coral reef surrounding the deposit effectively isolated the test deposit from other deposits.

The excavation of the craters and their subsequent readjustment after the field test caused some erosion of sand from the coral sand interface, resulting in the collapse and migration of reef fragments into the deposit. The level of the sand dropped one meter along one section of the coral/sand boundary. It is not known whether the exposed coral rock will eventually be colonized by marine organisms because the environmental studies were terminated before sufficient time for colonization was possible. However, the reef platform is predominantly composed of fragile dead fingercoral fragments (*Porites compressa*) which are not stable substrates for the colonization by corals. The slumping and collapse of coral due to undermining did not result in significant damage to the coral communities; however, the fragments which migrated down into the craters occasionally hampered the operation of the SSRS and there is both engineering and economic justification to avoid future sand excavations near reefs.

Results of the transect studies indicated no changes in the abundance and composition of coral communities attributed to test operations. However, the setting, dragging, and hoisting of anchors and the whiplash of mooring cables caused significant but localized damage to the coral communities. Also some corals were buried under the concrete clump used to anchor the steel delivery pipe at the shoreline. The anchor and cable damage was the most significant adverse effect to the reef communities.

The results of fish surveys and observations indicated the possible migration of reef fish populations towards the test site and the definite attraction of schools of goatfish to the immediate vicinity of the mining activity. It is of interest to note that the EIS (NOAA, 1974) predicted that fishes would probably avoid the test site during recovery operations. Schools of the goatfish (weke; *Mulloidichthys samoensis*) were reported feeding on the lug worm *Arenicola* and other worms as they became exposed during sand excavation. The project engineers also reported that the average size of the fishes increased noticeably during the two-month test period. The fish schools also lingered in the vicinity of the craters for at least several weeks after termination of the test.

Collections and censuses of shells at the slurry discharge pipe in the deposition basin indicated that the EIS substantially underestimated the size and diversity of mollusks inhabiting the deposit. Based upon the 1,200 shells and fragments collected, at least 34 genera and 78 species were recorded and most of these probably are adapted to living in sandy habitats. However, only 2 to 4 percent of the collected shells contained recently living tissue, thus it was difficult to determine the exact size of the living mollusk populations at the deposit. It seems safe to conclude that several thousand living mollusks probably inhabited the deposit. It is also important to note that the alternative methods for sampling the mollusks at the deposit failed to reflect the significance of the size and diversity of the populations--probably because of the cryptic and nocturnal habits of many mollusks. The destruction of the sand dwelling mollusks probably represents the most severe unavoidable impact attributed to the SSRS test at Keauhou.

The quadrat surveys of echinoderms in the coral thickets indicated considerable fluctuations in sea urchin population densities, but these could not be correlated with any natural or SSRS test factor. However many sea urchins were observed at the bottom of the craters after completion of the test. These sea urchins probably migrated across the deposit and fell or got trapped in the craters. Many urchins were buried and killed in the bottom sediments of the craters. It is not known whether the sea urchins remained in the craters for behavioral reasons or because of their inability to climb up the soft, steep walls of the craters. This impact could have a long-term effect on local sea urchin populations until the craters fill in.

Discussion

The EIS was able to correctly predict that turbidity generation would not result in significant environmental impact and that anchoring operations would damage coral reefs. However other impacts, including some significant ones, were underestimated or not predicted by the EIS. Thus, the environmental monitoring studies provided useful and additional insight into the environmental effects of the SSRS.

It is important to emphasize that most of the adverse impacts attributed to the SSRS operation can be avoided by using common sense precautions and advanced planning. Damage to corals from cables and anchors can be prevented by anchoring only in the sand, mining sand at deposits removed from coral formations, utilizing alternate mooring methods, and mooring only one vessel or barge to each anchor. Most of the damage at Keauhou will probably be only temporary since corals have considerable capacity to repair and regenerate itself. Damage to sand dwelling mollusks and sea urchins can be reduced by comprehensive surveys for these organisms at potential sand mining sites. The sites supporting the least developed mollusk and sea urchin populations could then be selected for sand mining. However, there will need to be a refinement of the methods used to estimate sand mollusk populations because existing methods frequently fail to estimate accurately the diversity and development of these organisms. In any case, the technique of censusing the slurry discharges at the deposition basin is still the most effective means to estimate mollusk populations and should be pursued vigorously in future applications of the SSRS.

There is also good reason to believe that the Keauhou site supported an exceptionally diverse and developed mollusk community compared with other sand deposits surveyed for potential sand recovery operations (Environmental Consultants, 1973a and 1973b). Thus, it seems likely that damage to mollusks at other locations may not be as severe if sites showing reduced mollusk development are selected for sand recovery.

Conversely, other impacts which were not significant at the Keauhou test could be significant at other sites, if proper precautions are not taken; these include:

1. Accidental breaks in the pipeline
2. The emergency use of backflushing to clear clogged lines
3. The unsuitability of sites as deposition basins
4. The potential erosion of beach sand reservoirs

The first potential impact can be reduced significantly by posting watches during sand mining operations and periodically inspecting pipes and equipment. The need to use backflushing of lines during a contingency can be reduced considerably by design improvements to crushers and other equipment and careful site selection of sand deposits where large shell, coral and other fragments are uncommon. The last two potential impacts can be prevented by selecting sites where suitable deposition basins can be established and where sandy beaches and their offshore reserves are not connected to the deposits to be mined. This can best be accomplished by advanced diving and beach surveys near prospective sites. It may also be worthwhile to perform another SSRS test offshore from a beach system (on a pilot scale) in order to document the effects of offshore mining operations.

Conclusions and recommendations

The SSRS has been shown to be an effective sand mining technique which minimizes the generation of turbidity and resuspended sediments--impacts which are caused by other dredging methods and which result in significant adverse impact to marine life. By utilization of advanced planning, surveys, design improvements, and other precautions, the SSRS holds promise as a sand mining technique compatible with the concept of environmental preservation and protection.

The field environmental monitoring studies at Keauhou have demonstrated that the environmental impacts predicted beforehand in EIS's can be substantially different in type and emphasis from those observed during mining operations. The environmental monitoring program and others to follow can provide valuable insight on potential environmental effects for proposed projects and can help to refine future EIS's and other planning tools. In this manner, the resource manager will be able to make more rational and objective decisions on the use of natural resources.

Experience gained at the Keauhou study indicates that monitoring studies are probably more valuable if a combination of both qualitative observations and quantitative surveys are considered. In the case of the Keauhou study, both types of approaches yielded valuable information and insight. In addition, the concept of using control stations, replicate sampling, and time-series monitoring studies will render environmental surveillance studies more informative and interpretive.

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Appendix B. Economics of Sand Recovery

by Jack R. Davidson

The sand recovery experiment produced approximately 12,000 cu yd of sand at a total cost (excluding SSRS research and development costs, but including cost of present system) of approximately $80,000.[1] This included environmental monitoring and local contribution to the environmental impact statement, but did not include cost incurred by federal agencies in EIS preparation and processing.[2]

The costs were higher than would be expected for future operations for several reasons: the extra (learning) costs associated with a first of its kind commercial-scale operation of the SSRS; the delays and downtime caused by replacement and repair of substandard surplus and second-hand components (necessitated by low equipment budgets); the learning costs associated with the first of its kind of operation of the platform-to-shore floating sand delivery system. In spite of the increased costs associated with the experimental aspects, the project can be considered an economic success. With delivered sand selling for $15 and up, revenues should exceed assignable costs by a comfortable margin even after state royalties.[3]

The following analysis is provided to show expected costs for a full-scale commercial recovery operation.

Two sizes of operation are shown: a small-scale 10,000-cu yd project (Table 1) similar to the recent experimental operation and operation at capacity for one year or about 100,000 cu yd of sand[4] (Table 2).

Costs of main components of the SSRS are shown below:

Equipment costs*	
Suction probe	
Hydraulic power unit	$ 7,850
Manifold--6 inches	1,076
Pumps and engines	1,685
Hoses	15,150
Pipeline--2,000 ft	3,980
Winch	9,000
Barge accommodations	1,000
	2,100
	$41,841

*1975 costs (estimated)

For subsequent analysis, a useful life of two years of full operations (200,000 to 300,000 yd) is assumed. Other costs include rental of a 50 ft long x 20 ft wide barge and a small tug to move anchors and the barge, etc.

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[1] F. Casciano, System Development Engineer, suggests a range of 100,000 to 150,000 cu yd of production for 10 months operation with two months downtime for major repairs, adjustments, storms, etc.

[2] Not determined at time of this writing.

[3] Not determined at time of this writing.

[4] See footnote 1 above.

TABLE B1. COSTS AND RETURNS ASSOCIATED WITH A 10,000-CU YD SAND RECOVERY OPERATION

Item	10,000 cu yd	per cu yd
Equipment costs	$ 2,093	$ .21
Crew	14,592	1.46
Mechanical costs	480	.05
Barge rental	1,500	.15
Tug rental @ $400 per day	4,800	.48
Skiff	102	.01
Scuba equipment	75	.00
Supplies and transportation	3,500	.35
Repairs	1,500	.15
Receiving basin preparation and sand handling at receiving point	10,000	1.00
EIS	5,000	.50
Environmental monitoring	10,000	1.00
	$ 53,642	$ 5.36

TABLE B2. COSTS AND RETURNS ASSOCIATED WITH A 100,000-CU YD SAND RECOVERY OPERATION

Item	100,000 cu yd	per cu yd
Equipment costs	$ 20,930	$ .21
Crew	126,464	1.26
Mechanical costs	7,200	.07
Barge rental	12,000	.12
Tug rental @ $400 per day	48,000	.48
Skiff	1,200	.01
Scuba equipment	600	.01
Supplies and transportation	35,000	.35
Repairs	15,000	.15
Receiving basin preparation and sand handling at receiving point	15,000	.15
EIS	5,000	.05
Environmental monitoring	15,000	.15
	$301,394	$ 3.01

(two days a week), and a 20-ft skiff to provide platform-to-shore linkup for personnel, fuel, and supplies.

Crew requirements include four men to operate the equipment in two overlapping shifts:[5] 6:00 a.m. to 2:00 p.m. and 10:00 a.m. to 6:00 p.m. and specialized mechanics at one week per month of operation.

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[5] The period of overlap provides time for refueling, minor repairs, and adjustments.

The capacity of the platform-to-shore floating delivery system without booster pumps appears to be about 2,000 ft of pipe. This depends, of course, on the height of the lift to the settling basin.[6] If the sand must be pumped more than 2,000 ft, an additional floating pumping platform would be needed. This may increase total operational cost to between 33 and 50 percent.[7]

This analysis will consider two situations: (1) recovery and pumping of 10,000 cu yd of sand to a shore settling basin, and (2) recovery and pumping of 100,000 cu yd of sand from a single site (total effective pumping distance less than 2,000 ft in each case). The basic unit (equipment, crew, support vessels, etc.) remains the same in each situation.

A total of six weeks would be required for situation (1). This includes one week set up and one week take down time per job. Assuming depreciation as a function of work performed, equipment costs in situation (1) would be based on 1/20 of useful life. Table 1 shows estimated costs of a contract to provide 10,000 cu yd from a single site at $5.36 per cu yd of sand delivered on shore.

Situation (2) involves a single site with a maximum 2,000-ft platform-to-shore sand delivery distance. Economics arise due to less set up-take down time (assumes 10 months pumping vs two months downtime) and essentially the same environmental assessment and monitoring requirements for a large vs small operation. Total annual equipment and operating costs are estimated at $301,394 or about $3.01 per cu yd of sand deposited on shore.

Extrapolating situation (1) costs to a total of seven operations to produce 70,000 cu yd of sand in a one-year period (seven months pumping time, three months take down time, and two months downtime) would cause costs to decrease to about $4.05 per cu yd.[8] Although the latter situation represents an extreme condition (i.e., seven small operations at separate sites, full environmental assessment and monitoring and holding basin development at each site, etc.) it serves to illustrate the magnitude of cost economics to be expected as the recovery operation is extended. Small deposits, existence of limits on the amount which can be taken at a certain location, etc., would tend to drive costs up sharply.

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[6] This should be considered a rough rule of thumb. The breakoff points between distance and other variables can be estimated theoretically.

[7] For distances over 2,000 ft, total cost for use of floating pipeline and booster units should be compared with cost of using a barge to receive, transport, and discharge sand on shore.

[8] Additional savings might be realized on small jobs involving beach restoration of the sand which could be pumped directly on shore, eliminating the cost of developing a holding area.