CWP-XR-0001

TUNNELING AND DRILLING FOR OTEC COLD WATER PIPES

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Energy Technology Engineering Center

Operated for the U.S. Department of Energy
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TUNNELING AND DRILLING FOR OTEC COLD WATER PIPES

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ABSTRACT

This report summarizes the results of a study to determine the feasibility of using a tunnel or large-diameter drilled shaft as a conduit for transporting cold water from an ocean depth of 2000 ft to an ocean thermal energy conversion (OTEC) plant located on shore. The report identifies five possible cold water pipe (CWP) approaches that are dependent on the geologic formation and hydrology of the site.

For this survey, the site under consideration is Keahole Point on the west coast of the big island of Hawaii. The site was chosen because of the easy access to deep cold water provided by the steep offshore slope, the proximity to air and sea transportation, and the availability of land.

The survey concludes that although many site-specific factors must be considered, tunneling or drilling is in general a viable option for meeting the long-term OTEC cost goals.

This study was carried out for the United States Department of Energy (DOE) by the Energy Technology Engineering Center (ETEC) as part of the OTEC Cold Water Pipe Technology program.

I. EXECUTIVE SUMMARY

This report summarizes the results of a study to determine the feasibility of using a tunnel or large-diameter drilled shaft as a conduit for transporting cold water from a >2000-ft depth in the ocean to a shore-based ocean thermal energy conversion (OTEC) power plant. The study was carried out for the United States Department of Energy (DOE) by the Energy Technology Engineering Center (ETEC) as part of the OTEC Cold Water Pipe (CWP) Technology program.

The CWP presents the most challenging engineering aspect of a land-based OTEC plant. CWP installations require careful attention to site selection, environmental loading, and geotechnical considerations for foundation integrity. Although large-diameter pipes (>10 ft) have been fabricated, they have only been installed in shallow near-shore water. Installation of large-diameter, bottom-mounted pipe in deep water is beyond the currently demonstrated capability of the industry.

To address these issues, ETEC was awarded the CWP Technology program by DOE. The purpose of this program is to investigate the design, construction, and deployment of CWP systems, with the intent of reducing their capital costs. The effort includes investigations of materials of construction and methods of deployment for various designs. Additionally, system components are being considered that could be common to several configurations. The results of these investigations will lead to generic CWP components suitable for assembly with various CWP configurations.

Several pipe designs and materials have been considered. The materials investigated included steel, reinforced concrete, and fiber-reinforced plastic. All these materials raise questions about the size of the pipe that can be built and deployed at the depth required. A seafloor-mounted pipe and its supports must be designed to bridge escarpments and bottom irregularities while withstanding hydrodynamic loading caused by currents and waves.

Because of the difficulties anticipated in the deployment of large piping systems, ETEC investigated the prospect of drilling and/or tunneling as an alternative way to provide a conduit for water transport. For this study, the site considered was Keahole Point on the west coast of the big island of Hawaii. The site was chosen because of the easy access to deep cold water provided by the steep offshore slope, the proximity to air and sea transportation, and the availability of land.

A preliminary model of the geologic structure of Keahole Point has been developed (Figure 1). This model divides the island into five principal rock types: (1) thin lava flows, which make up the subaerial shield volcanos; (2) an underlying pyroclastic layer composed of littoral ash, hyaloclastite fragments, and erosional detritus; (3) pillow lavas and pillow fragments erupted in intermediate to deep water, which make up the majority of the

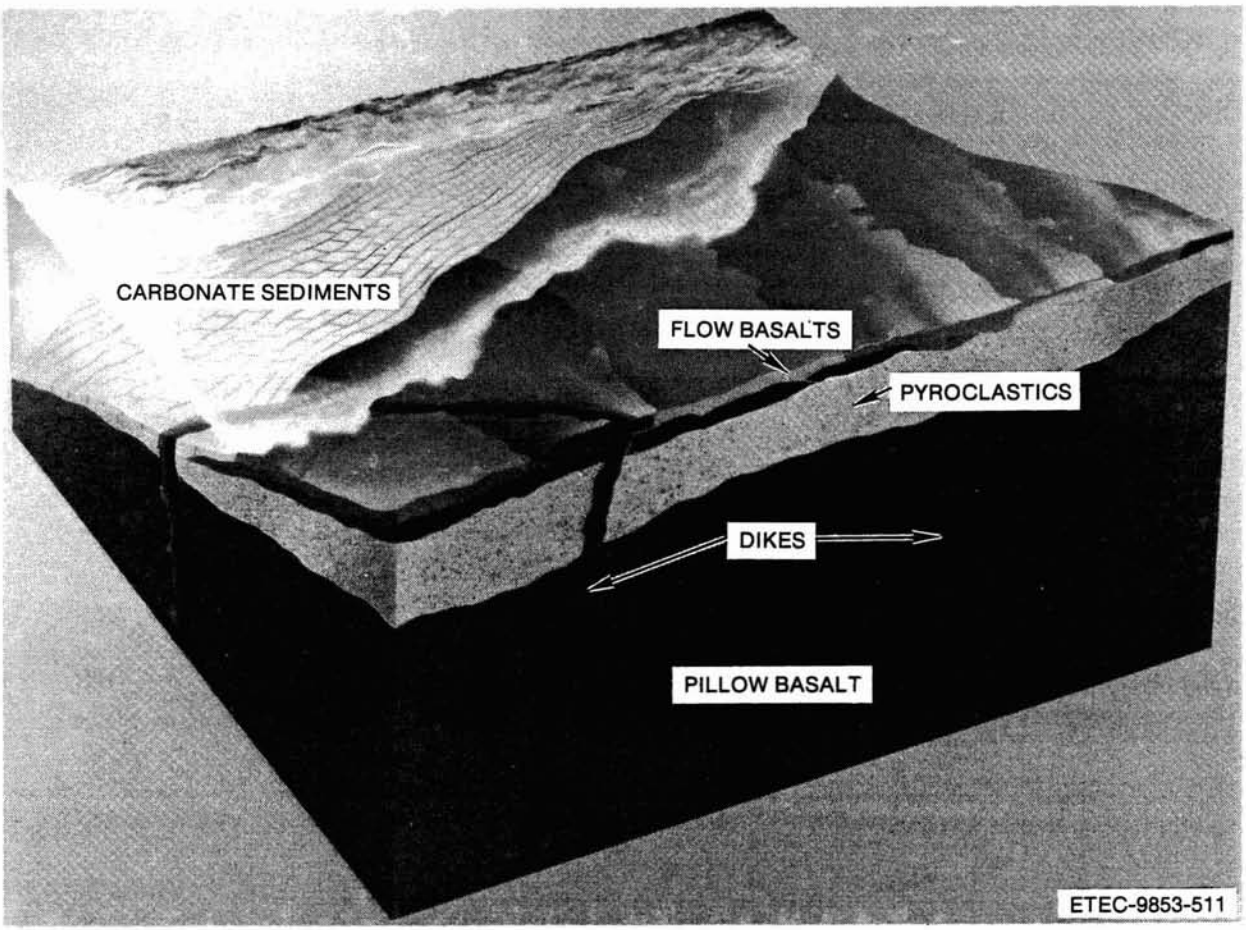

Figure 1. Preliminary Geologic Model--Keahole Point

island mass; (4) carbonates; and (5) dense dike and plug complexes. Testing and verification of this model will require geophysical surveys (seismic surveys in particular) and a deep drilling program.

Several companies with expertise in drilling and tunneling technology were contacted. The results of these contacts indicate that five different drilling or tunneling concepts are applicable to the OTEC program:

- Pumping a vertical shaft. This concept is the least expensive and has the potential to exceed the long-term OTEC multiyear program plan CWP cost goal but would require a good natural conduit between the cold ocean water and the vertical shaft. Very preliminary geological information from geothermal wells on the island of Hawaii indicate that such a natural conduit may exist.

- Slant drilling. Current technology exists for slant drilling holes up to 26 in. in diameter, which, in turn, can be reamed up to 60 in. in diameter. However, development would be needed to slant drill 10-ft-diameter holes. Slant drilling has the potential to meet long-term CWP cost goals.

- Tunneling. A 10-ft-diameter tunnel made by machine has the potential to exceed the intermediate-term cost goals with current technology. Current tunneling technology can provide a 14-ft-diameter tunneling machine for about the same cost as a 10-ft-diameter tunneling machine. Tunneling can be performed at most known OTEC sites and can be extrapolated up to 36 ft in diameter with current technology. Development is needed for tunnels deeper than 1000 ft in porous media.

- Down and out. In this tunneling concept, a vertical shaft is run to about 2300 ft, at which point a lateral shaft with a slight upward slope is cut to the ocean bottom. This is a standard tunneling method using existing technology that, although longer, could provide some logistic and, hence, cost advantages.

- Mixed effluent discharge. Preliminary geology information suggests that large fissures may exist near the surface at Keahole. A shallow (about 300 ft) vertical hole, therefore, has the potential to provide a less expensive mixed effluent discharge than a separate pipe to the same depth in the ocean.

Combination concepts are also possible. For instance, insertion of a pipe through a shallow tunnel reduces hydrodynamic and deployment loads of the pipe and could reduce the high cost of trenching under water and of sea deployment.

Each concept is based on several assumptions about the site (e.g., geology and hydrology). At the surface, the lava is very porous and highly permeable. Communication to the ocean is expected to exist. However, it is not known if this communication exists at the depth required for cold water collection (deeper than 2000 ft). Ultimately, the approach chosen and the resultant design of the shaft (whether drilled or tunneled) will depend on the geology, hydrology, and geomechanics of the lava deposits at Keahole Point.

An exploratory test hole at Keahole is necessary before any of the drilling or tunnel boring concepts can be thoroughly evaluated. This test hole should be 9 to 12 in. in diameter and at least 3000 ft deep. This test hole has several purposes:

- Determine precise geology at a selected site
- Determine the porosity and permeability of selected geologic zones
- Determine the flow rate limit of a vertical hole
- Determine the temperature of water from a pumped vertical hole
- Test the mixed effluent discharge concept.

Depending on the outcome of the geologic and hydrologic tests on the vertical test hole, consideration should be given to a slant-drilled test hole. Although geologic conditions may not vary significantly with depth compared with the vertical hole, a slant hole will provide the data needed to assess the viability of slant drilling or tunneling. This test is mandatory if no communication between the vertical shaft and ocean exists.

The data indicate that it will be impossible to meet the long-range OTEC cost goals using conventional (bottom-mounted) technology. It appears, however, that tunneling or drilling a large shaft is a viable alternative to the providing of a water conduit capable of meeting the cost goals. The technology exists, although development is needed to provide remote operation capabilities for areas where water intrusion rates are high.

II. INTRODUCTION

Ocean thermal energy conversion is a technology for producing electrical energy from the solar energy collected and stored as heat in warm ocean water. Although OTEC has the potential to provide a considerable fraction of the electrical power requirements of areas of the United States located in proximity to tropical waters (see Figure 2), several technical advances will be required to make OTEC cost competitive with conventional sources of electricity. Capital cost for an OTEC plant is very high and although all components contribute to the high cost, the seawater pipes (cold, warm, and mixed disposals) represent between 40 and 80% of the total plant cost.[1] Therefore, approaches that reduce CWP costs can have a major impact on the viability of the OTEC technology.

Several plant types have been suggested. Figure 3 illustrates the land-based (or shallow-water), shelf-mounted, floating, and moored plant types relative to the land/ocean floor profile. The floating plant with a suspended CWP has the most potential sites. However, major unresolved issues exist concerning the effect of ocean dynamics on the CWP/platform connection. Both the floating and the moored plant types have disadvantages related to product transportation. Such issues are either nonexistent or less severe for a land-based plant.

A land-based OTEC power plant offers several advantages. First, no subsea cable is required, since the power is delivered directly to a local grid. Second, the problem of dynamic loading caused by waves and current is avoided. Third, the construction, operation, and maintenance of the plant are much simplified. Fourth, plant availability and, hence, plant economics are improved.

The CWP presents the most challenging engineering aspect of a land-based OTEC plant. Although large-diameter (>10 ft) pipes have been fabricated, they have only been installed in shallow near-shore water. The installation of large-diameter pipe in deep water is beyond the currently demonstrated capability of the industry.

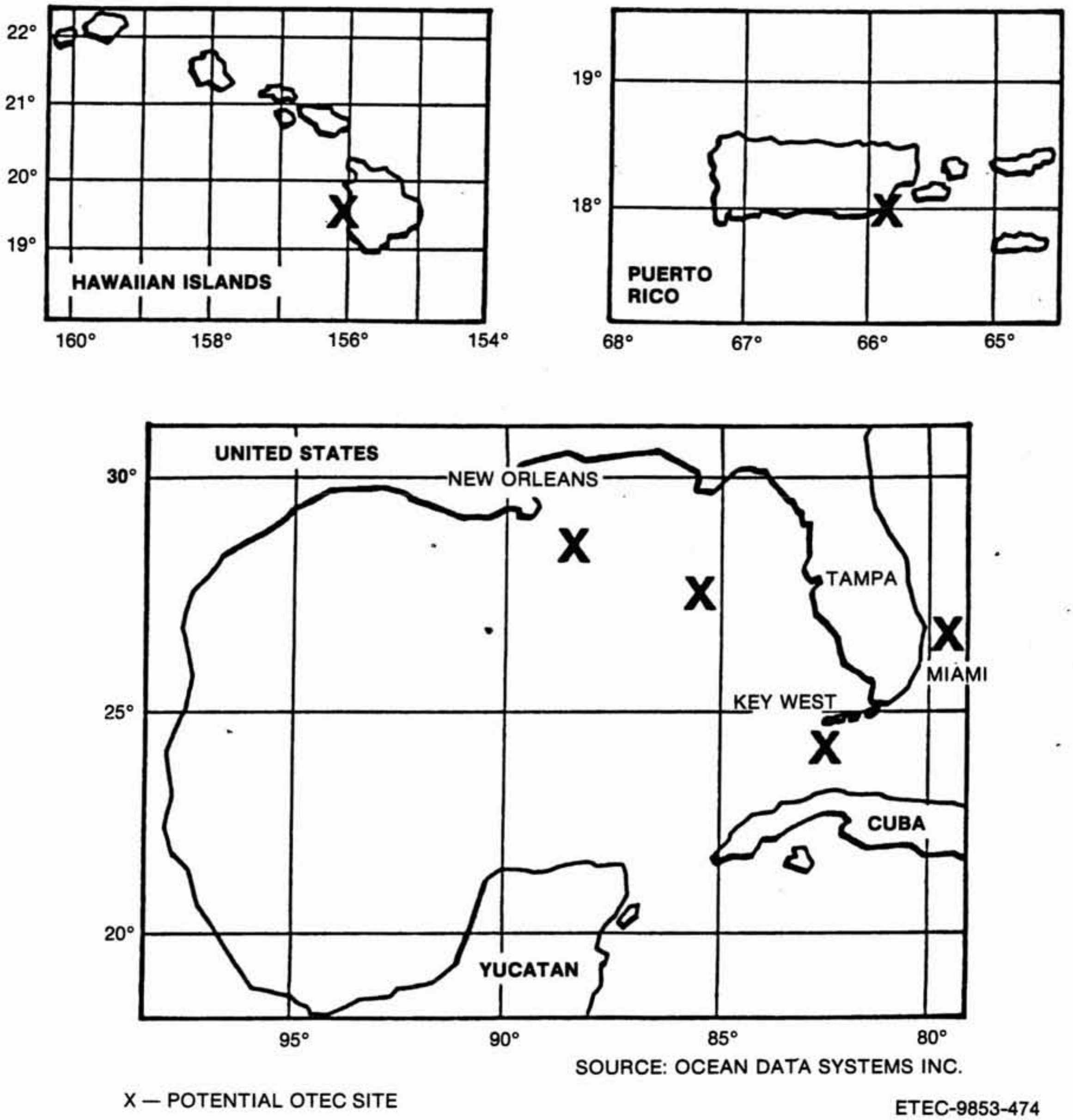

Figure 2. Location of Potential OTEC Sites

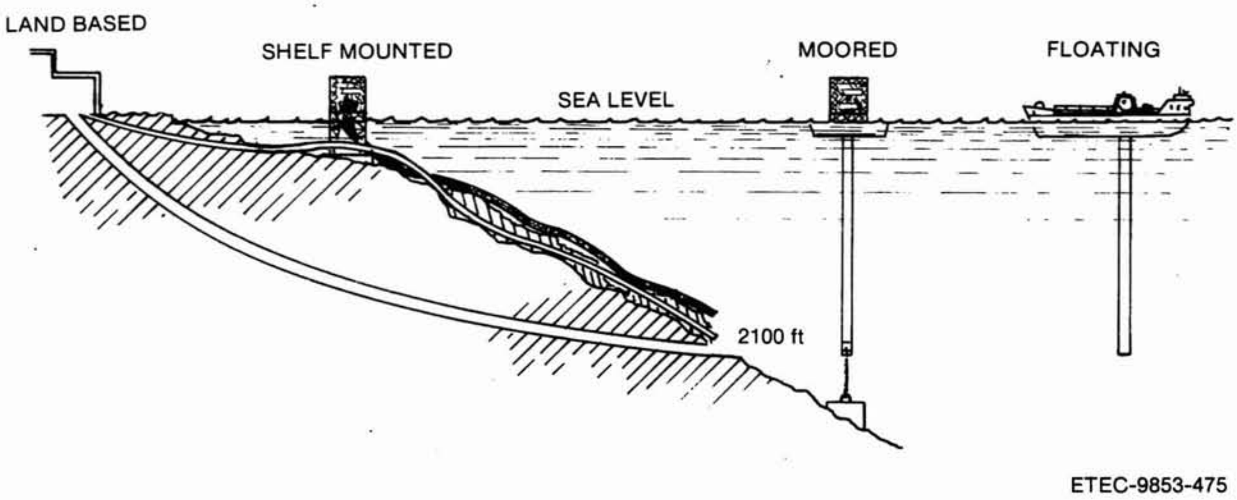

Figure 3. OTEC Plant Types

The DOE CWP technology program seeks to provide information on the design, construction, and deployment of large CWP systems and associated components. The program is described by the simplified sample matrix of Figure 4. This matrix shows several configurations and their applicability to bottom characteristics. Each "X" represents a component or element of a configuration that overcomes the given ocean characteristic. The absence of an "X" indicates that the given configuration probably is not applicable to that characteristic. For each "X," quantitative cost algorithms of CWP element cost as a function of pipe diameter, material, deployment, depth, and the like will be developed. As part of this program, ETEC investigated the prospect of drilling and/or tunneling as an alternative to the providing of a conduit for water transport.

To survey drilling and tunneling methods, ETEC directly contacted prominent organizations in the geology, drilling, and tunneling fields. The organizations contacted are listed in Table 1.

For this survey, the site under consideration is Keahole Point on the west coast of the big island of Hawaii (Figure 5). Located in the district of North Kona, Keahole Point is approximately 9 miles north of the town of Kailua Kona and 23 miles south of the deep-water port of Kawaihae (Figure 6). The Kailua area is the major population center on the west side of the island.

	CHARACTERISTICS OF OCEAN																
	ON OR NEAR SHORE		SHALLOW WATER REGION (0-100 ft)			MID DEPTH (100-650 ft)					GREAT DEPTH (650-3000 ft)						
	ON SHORE	PUMP CHAMBER	SHALLOW WATER TO PUMP INTERFACE	SHALLOW WATER (SOFT)	SHALLOW WATER (ROCK)	SHALLOW WATER TO MID-DEPTH INTERFACE	SHALLOW SLOPE 0-15° (SOFT)	HIGH SLOPE 15-60° (ROCK)	CLIFF 60° SLOPE (ROCK)	BOULDER FIELD	RIDGE	SHALLOW SLOPE 0-15°	HIGH SLOPE 15-60°	CLIFF 60° SLOPE (ROCK)	BOULDER FIELD	DEEP WATER ANCHOR	OTHER
INVERTED STANDPIPE							X	X	X	X	X	X	X	X	X	X	X
CABLE LAY	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
TUNNEL	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SLANT DRILL	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SOFT PIPE						X	X	X	X	X	X	X	X	X	X	X	X
BOUYANT (CATENARY)						X	X	X	X	X	X	X	X	X	X	X	X
STEEL EMBEDDED IN CONCRETE	X	X	X	X	X	X	X										
ABOVE EARTH STEEL AND FOUNDATION	X	X	X	X	X	X	X	X	X	X							
BURIED STEEL	X	X		X	X	X	X										
CONCRETE BLOCK	X	X	X	X	X	X											
STEEL	X	X	X	X	X	X	X	X	X	X							
POURED CONCRETE	X	X	X	X	X	X											

QUANTITATIVE COST ALGORITHMS AS A FUNCTION OF DIAMETER, DEPLOYMENT, MATERIAL, AND DEPTH ARE TO BE DETERMINED AT X's

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Figure 4. CWP Technology Component Matrix

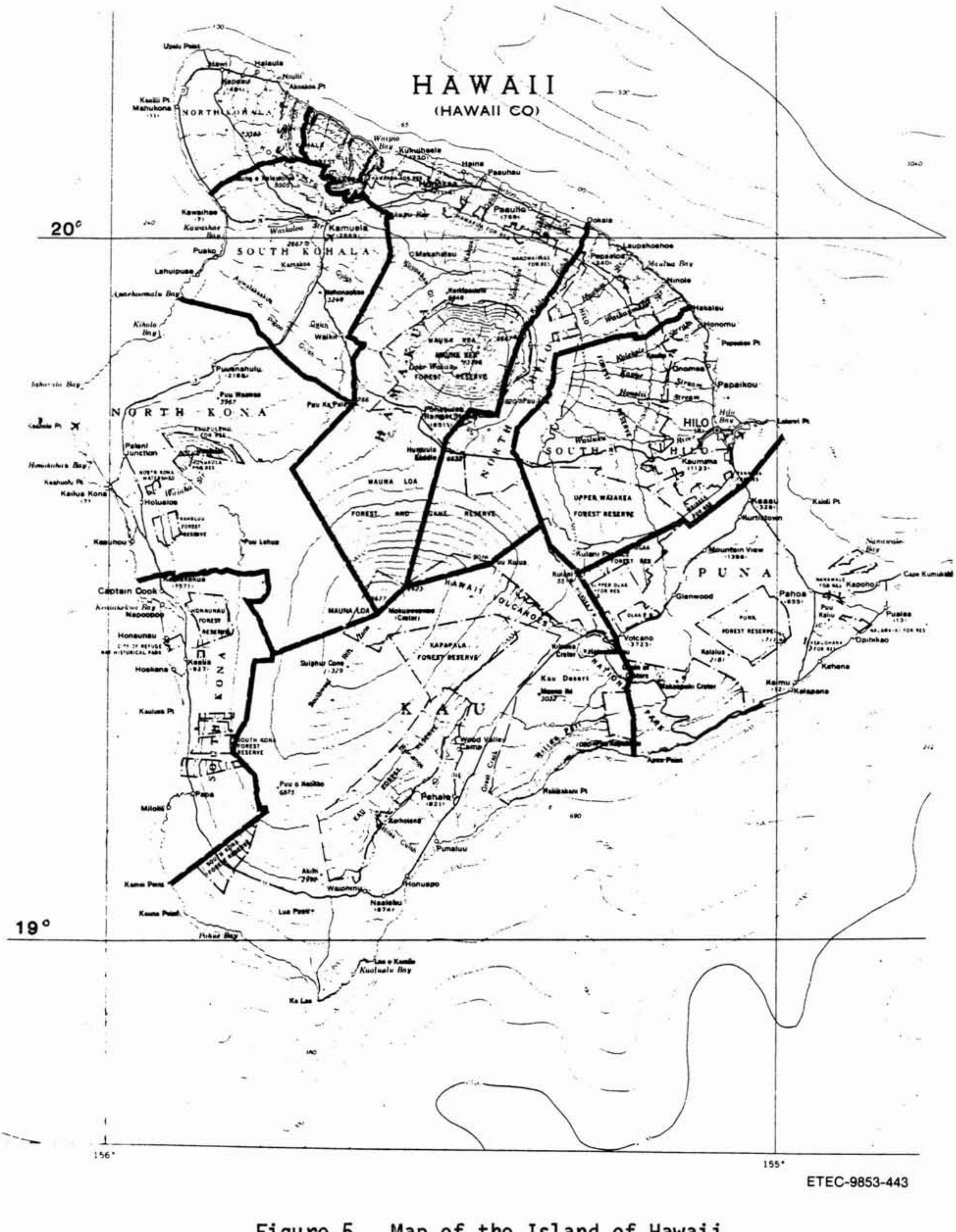

Figure 5. Map of the Island of Hawaii

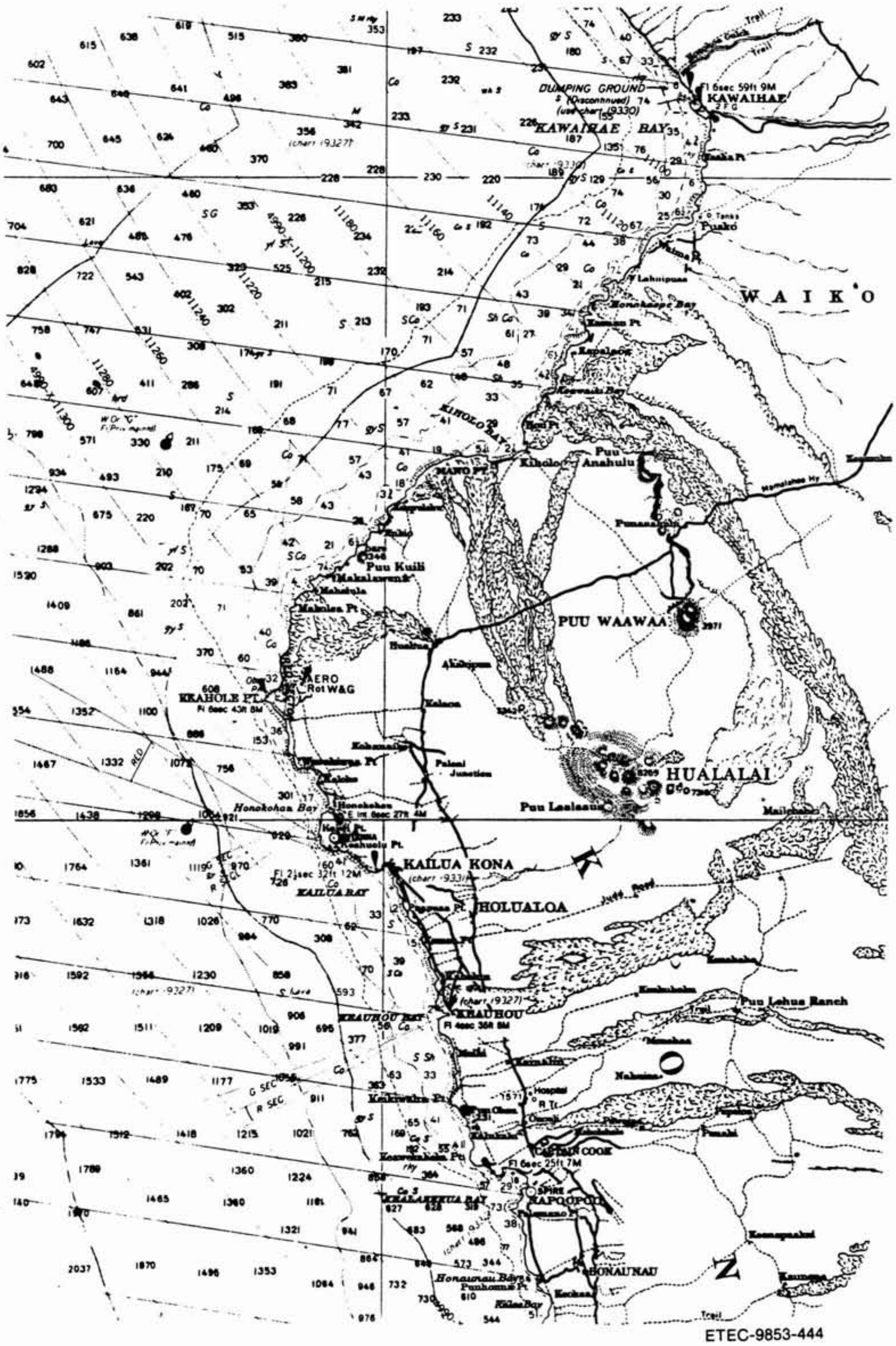

Figure 6. Map of Keahole Point

TABLE 1

APPROACH TO CWP TECHNOLOGY DRILLING/TUNNELING AND ORGANIZATIONS INTERVIEWED

Approach

- Survey prominent companies and organizations in geology and drilling/tunneling fields and determine the state of the art and preliminary costs

Organizations interviewed

- University of California
- USGS for the Pacific Basin
- University of Hawaii
- Reynolds Electric and Construction (Nevada Test Site)
- Santa Fe Shaft Mining Company
- Hughes Tool Company
- Rockwell International (Hanford)
- Robbins Company
- Smith International
- Eastman Whipstock
- Dailey Directional Services
- LOR, Inc.

Conferences attended

- Off-Shore Technology Conference
- Institute of Shaft Drilling Conference

The site was chosen because of the easy access to deep cold water provided by the steep offshore slope, the proximity to air and sea transportation, and the availability of land.

In 1974, the State of Hawaii set aside 328 acres of state-owned land at Keahole Point for research into renewable energy resources. Over the next decade, laboratory facilities were built, and a 1-mile-long, 12-in.-diameter pipeline was installed to bring water from a depth of 1925 ft into the laboratory. Figure 7 is an aerial view of the Seacoast Test Facility (STF) on Keahole Point.

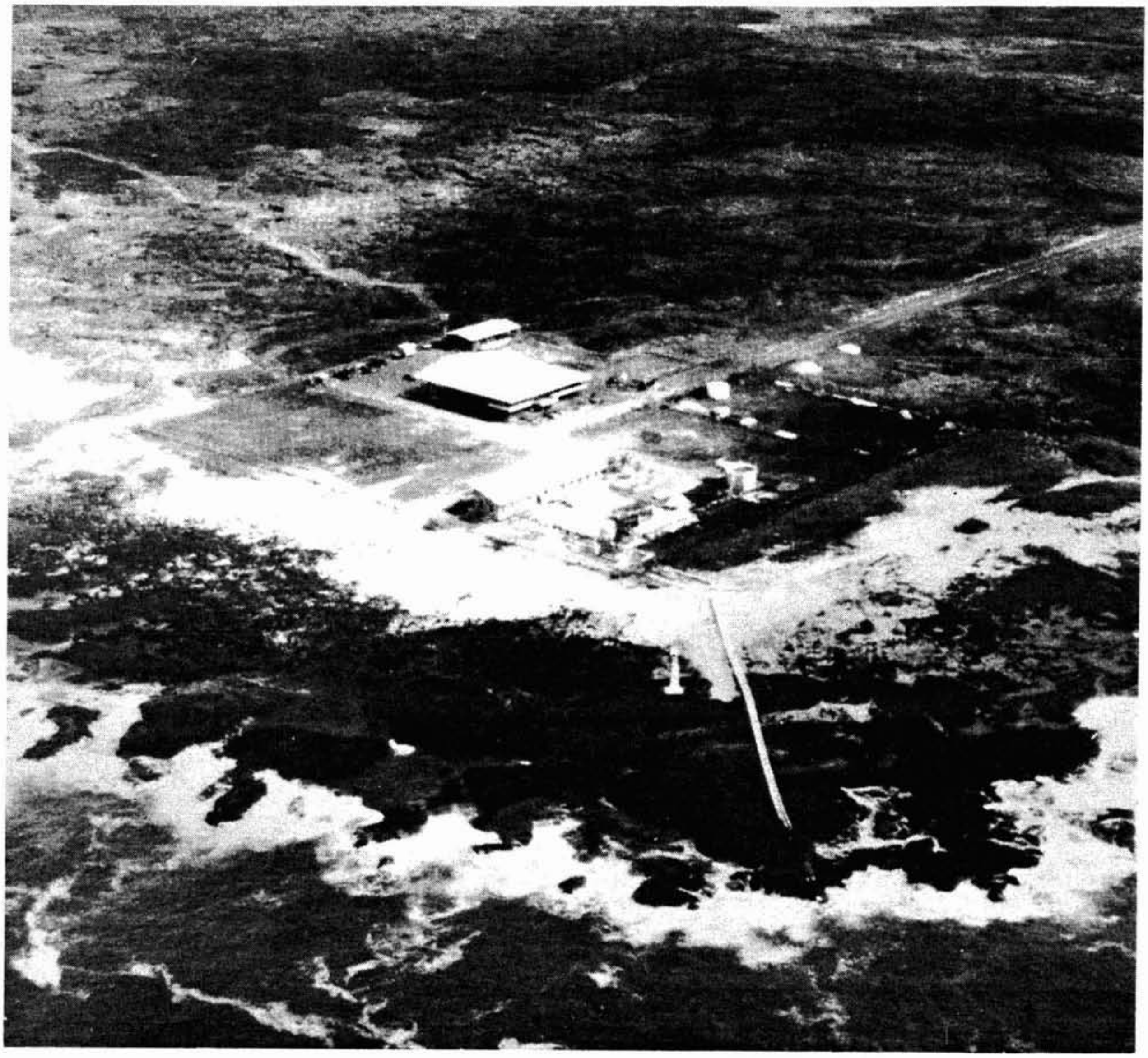
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Figure 7. Aerial View of STF

The objectives of the OTEC CWP technology program and the approach taken to complete it are described in Section III, and Section IV presents drilling and tunneling techniques currently used in the oil industry and in large-shaft installations for nuclear testing and nuclear waste disposal.

Section V summarizes drilling and tunneling concepts for this application, and Section VI presents the conclusions and recommendations for testing the geologic, hydrologic, and geomechanic properties of the area.

III. OBJECTIVES AND COST GOALS

The objective of the ETEC CWP technology effort for the DOE OTEC program is to establish new and generic CWP design concepts that reduce uncertainty and cost and improve service life. This objective comes directly from the OTEC multiyear program plan (MYPP). There is no restriction on the type of CWP configurations to be used. This report surveys drilling and tunneling concepts to meet the MYPP objectives.

The cost goals for the OTEC CWP are given in Table 2. The proposed concept should be able to be scaled to larger sizes and be usable at a variety of sites such as Puerto Rico, Hawaii, and American Samoa.

TABLE 2
OTEC CWP COST GOALS IN PROJECTED CAPITAL COST ($/kWe)
FOR A 10-MWe OTEC POWER PLANT

	Present Technology	5-Year Target		Long-Term Target	
Subsystem type	Closed cycle	Closed cycle	Open cycle	Closed cycle	Open cycle
Seawater CWP	5000	3600	3630	1410	1250

Cost estimates were obtained for the Natural Energy Laboratory of Hawaii (NELH) existing 1-ft-diameter CWP and projected 3-ft-diameter CWP. These two plus the pilot-plant (PP) preliminary design (20 ft in diameter) yield three CWP cost data points:

- NEHL 1-ft CWP $ 1M
- STF 3-ft CWP $ 4M
- PP 20-ft CWP $112M

These three data points indicate the cost of CWP scale approximately to the 1.6 power based on diameter:

$$\text{Cost (M\$)} = (D_{ft})^{1.6} \quad .$$

This implies that a 10-ft-diameter CWP, using state-of-the-art marine construction techniques, would cost $37M, or about $3700/kW installed. The $3700/kW is almost four times the long-term DOE target of $1000/kW. Cost optimization of existing design techniques might reduce the cost by 20 to 30%, but this is countered by the fact that a first-of-a-kind construction project usually costs more than the estimate. This means that the $1000/kW target for a 10-ft CWP would be impossible using conventional technology. New and innovative concepts are therefore sought.

IV. DRILLING AND TUNNELING TECHNOLOGY

This section describes the technology and equipment for drilling and tunneling. This information was collected during conferences with several drilling and tunneling companies (e.g., Santa Fe Drilling; LOR, Inc.; Hughes Tool Company; Smith International; Eastman Whipstock; Reynolds Electric and Construction; Dailey Directional Services; and the Rockwell International Basalt Waste Isolation Project group).

A. VERTICAL SHAFT DRILLING

The technology and equipment exist for drilling large-diameter vertical holes. The technology evolved from the requirements at the Nevada Test Site (NTS) in Mercury, Nevada. Because of the ban on the atmospheric testing of nuclear devices, the former Atomic Energy Commission established a requirement to perform the tests at the bottom of deep, large-diameter drilled shafts that had been backfilled. At the start of the program, the shafts were drilled using techniques from oil field technology. It soon became apparent that new systems would be needed to meet the increased load and torque demands of the deep, large-diameter holes required for the tests.[2]

In the early days of NTS large-shaft drilling, the method used was to drill a 30-in. hole and then underream in one or more passes to the desired final diameter. However, if the target diameter was fairly large, this process could take considerable time as the number of passes increased. To expedite operation, a large-diameter bit was developed.

As the hole diameter increased, conventional oil-field-type rigs were no longer adequate. The hoisting system on a large-diameter shaft drill rig must support the weight of the drill pipe and the bottom hole assembly (e.g., bit body, mandrel, stabilizers, and cast-iron donut weights). The deeper the shaft to be drilled, the greater the weight of the drill pipe that must be supported by the drill rig and, therefore, the less weight that can be allocated to the bottom hole assembly. The characteristics of the specific rock to be drilled will determine how much weight must be applied to the cutter to fracture the rock. Additionally, the torque required to turn the bit must be no more than the capability of the given rig. Figure 8 shows the 96-in. bit used at NTS on the Ideco 2500 drill rig. This rig is capable of drilling holes 72 to 140 in. in diameter to a depth of 4000 ft. The rated capacity of its 158-ft pyramid mast is 1.4×10^6 lb. Figure 9 is the Hughes-Micon CSD 300 rig, which is capable of drilling holes 20 ft in diameter to depths in excess of 3000 ft. Six hydraulic motors in the power swivel produce a torque of 500,000 ft lb to rotate the bit. Hoisting is accomplished by four hydraulic cylinders, each with a capacity of 500,000 lb, yielding a total rig capacity of 2×10^6 lb.

The downhole drilling assembly consists of a drilling mandrel, drill bit, stabilizers, and weights (Figure 10). The drilling mandrel is a heavy wall section of pipe used to hold the various components together. The bit is bolted onto the bottom of the mandrel. Stabilizers, either rotating or nonrotating, are added to control deviation during drilling. Rotating stabilizers are designed to rotate with the drilling assembly. Nonrotating stabilizers are designed to remain stationary as the drilling assembly rotates within it, which offers better protection against hole deviation. Ideally, a stabilizer should be placed as close to the bit as possible, and in addition, a second stabilizer should be placed at the top of the mandrel.

The total weight of the drilling assembly can be varied by adding or subtracting weights. The weights, referred to as "split donut weights," are stacked throughout the length of the mandrel. The weights serve two purposes. First, they create the necessary weight for cutter penetration. Second, they produce a "plumb bob" effect to help keep the bit on course. To ensure receiving the benefits of the plumb bob effect, only about 80 to 90% of the available weight is allowed to be on the bit. Figure 11 illustrates a typical flat-bottom bit body with roller cutters. As the drill pipe rotates the bottom hole assembly, the weight is transferred to the teeth of the individual roller cutters, which results in the fracturing of the rock from the formation. Typical drilling rates range from 5 to 7 ft/h in soft (<25,000 psi) formations to 1 ft/h in hard (50,000 psi) material.

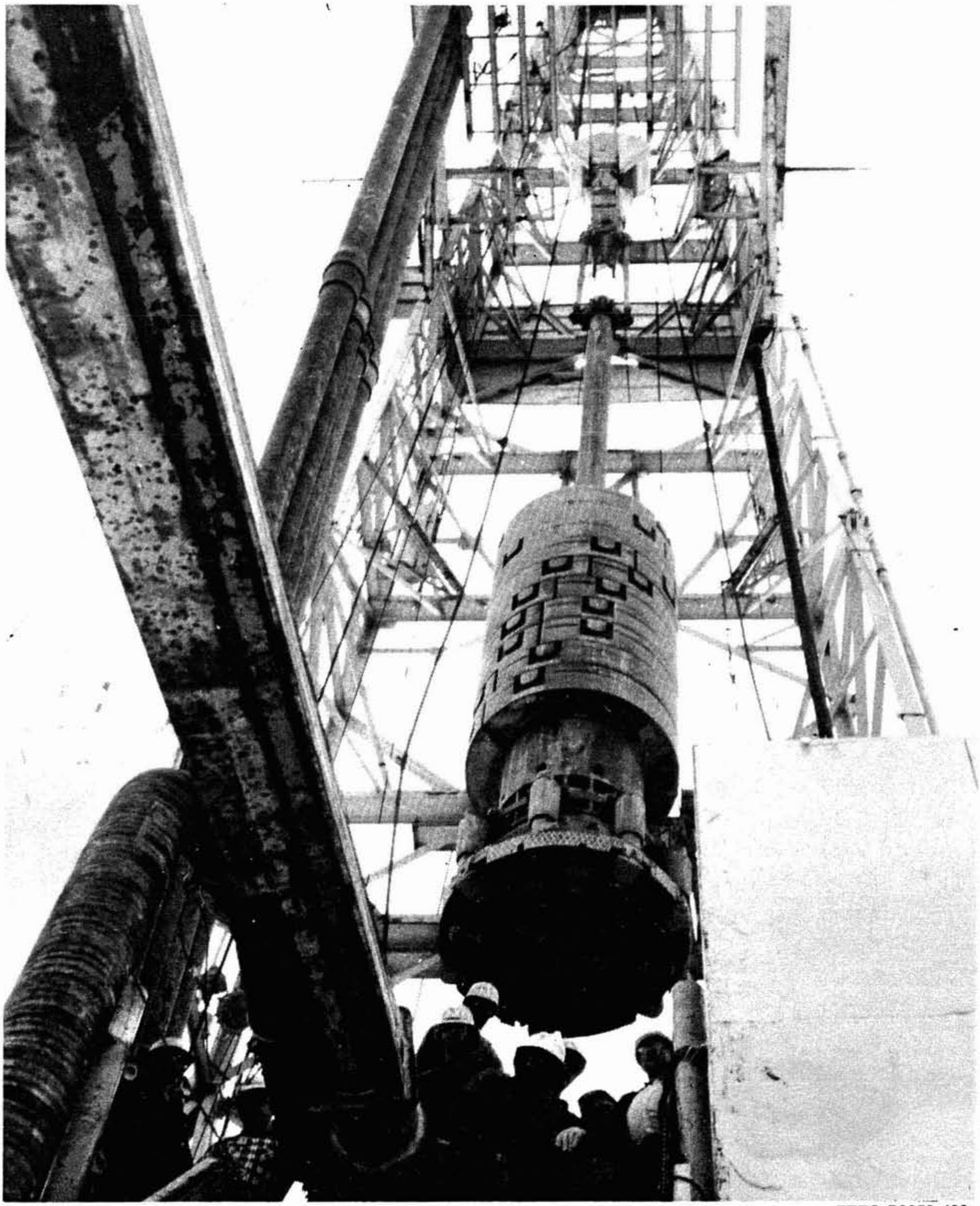

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Figure 8. Ideco 2500 Drill Rig

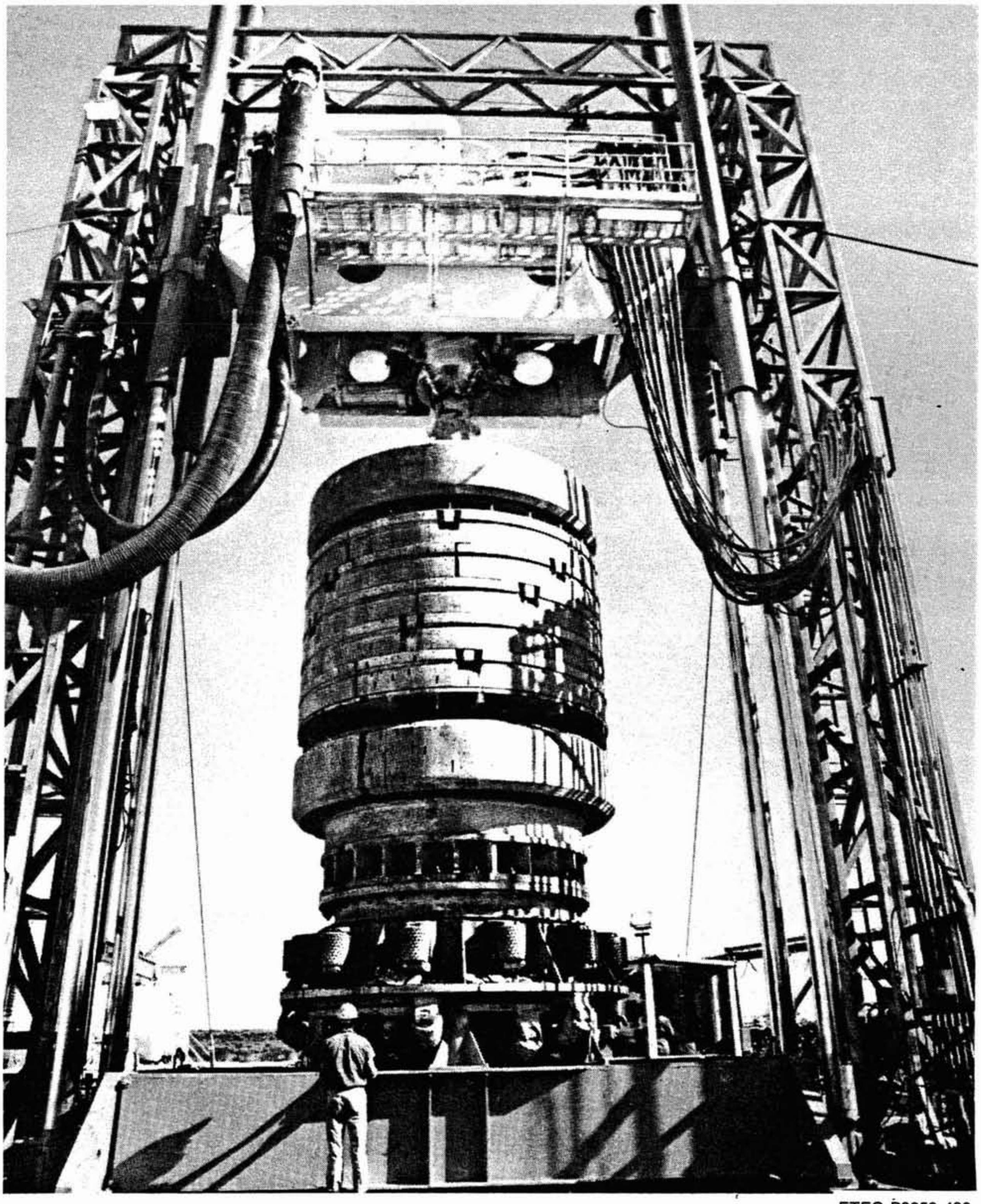

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Figure 9. CSD 300 Hughes Micon Drill Rig

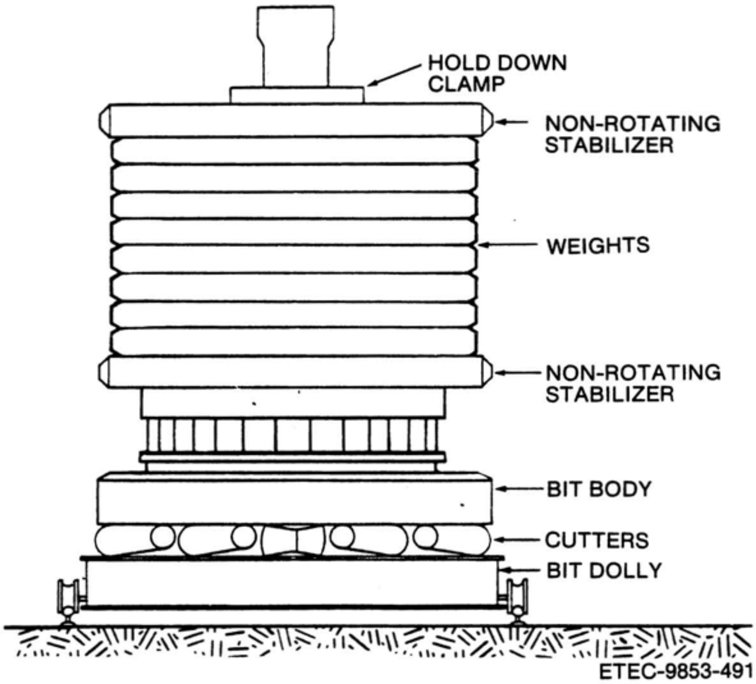

Figure 10. Bottom Hole Assembly with Nonrotating Stabilizers

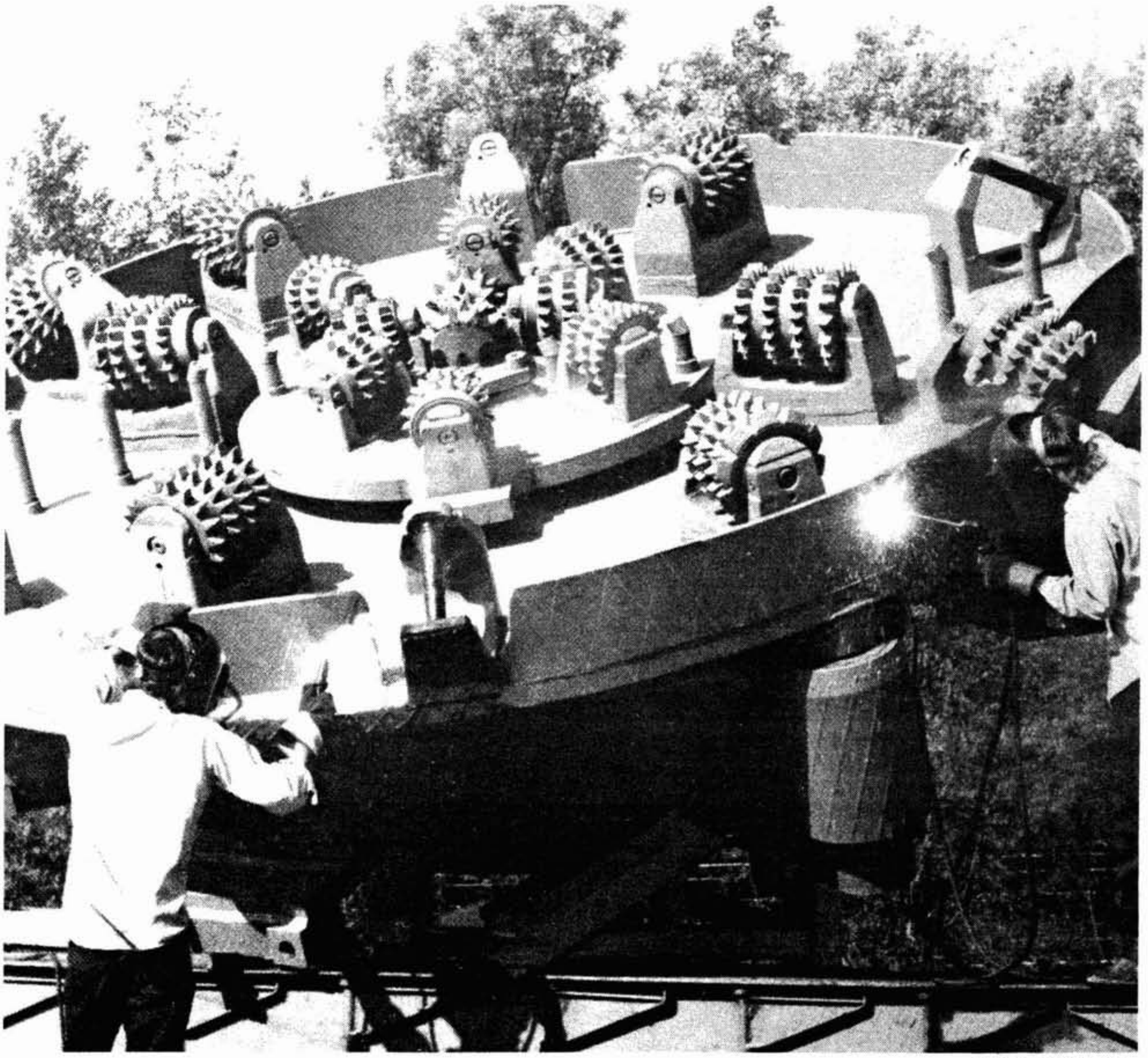

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Figure 11. Typical Flat Bottom Bit Body

Several types of roller cutters are available for use on large-shaft drilling bit bodies. Steel tooth cutters, as shown in Figure 11, are normally used when drilling holes in rock formations having compressive strengths up to about 15,000 psi. These are available with long teeth for drilling softer formations and short teeth for harder formations. For very hard rock formations, carbide insert cutters (Figure 12) are typically used. The carbide inserts, which are available in various shapes and lengths, may be either uniformly "scattered" across the cutting surface or symmetrically lined up so that rows of inserts run in specific paths as the roller cutter rotates. The cutter assemblies consist of a central core, which contains the lubricated bearings and a shaft for connecting to the saddle mounts.

Most large-diameter shaft installation projects use two bit bodies on the job site. When the penetration rate slows down significantly, it normally indicates that the roller cutters are becoming dull. This typically occurs after they have been rotating on the bottom for about 120 to 150 h. The bottom hole assembly is then brought to the surface, where the bit body is removed and replaced with a second bit body that has been dressed with a new set of cutters. The bottom hole assembly containing the new cutters is then returned to the hole to resume drilling operations. The used cutters are then checked to determine which ones must be replaced.[2]

Operators at NTS found that replacing the bit body at 80-h intervals greatly increased cutter and bearing life and significantly decreased overall cost to the project. Cutters could then be repaired, bearings greased, and the assembly serviced. While a new cutter costs about $4000/unit, service and repair costs were estimated at only $1500/unit. Cutters can be reserviced about 10 or 11 times.[2]

Once the rock particles have been broken from the formation, they are removed from the bottom of the shaft and brought to the surface by using a system called "reverse circulation." With reverse circulation, the drilling fluid and cuttings are returned up the drill pipe to the surface by using an air system to lift the fluid up the drill pipe. As illustrated in Figure 13,

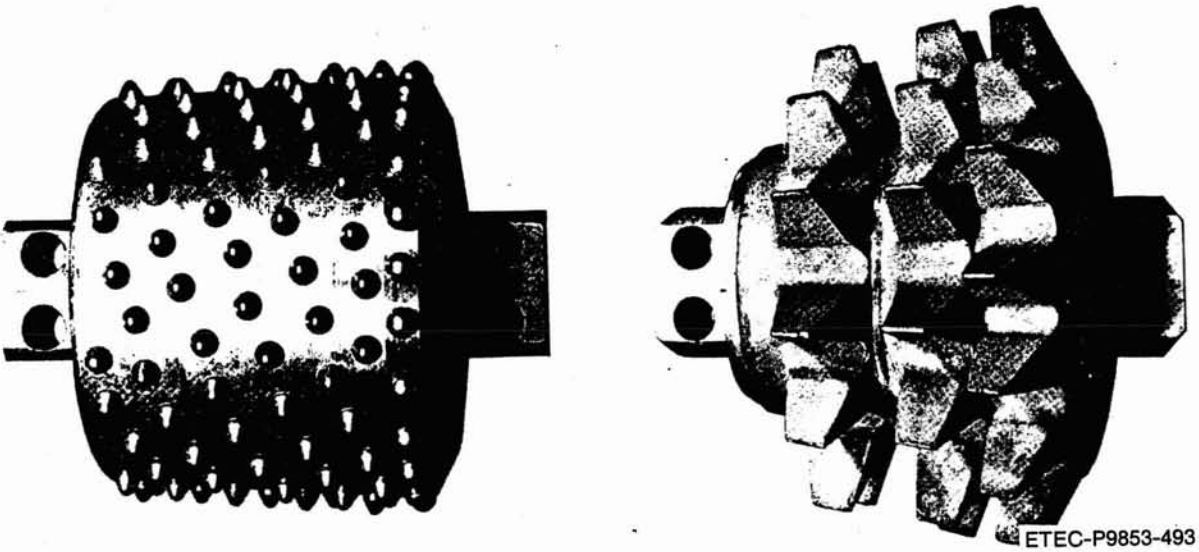

Figure 12. Carbide Insert and Steel-Toothed Cutters

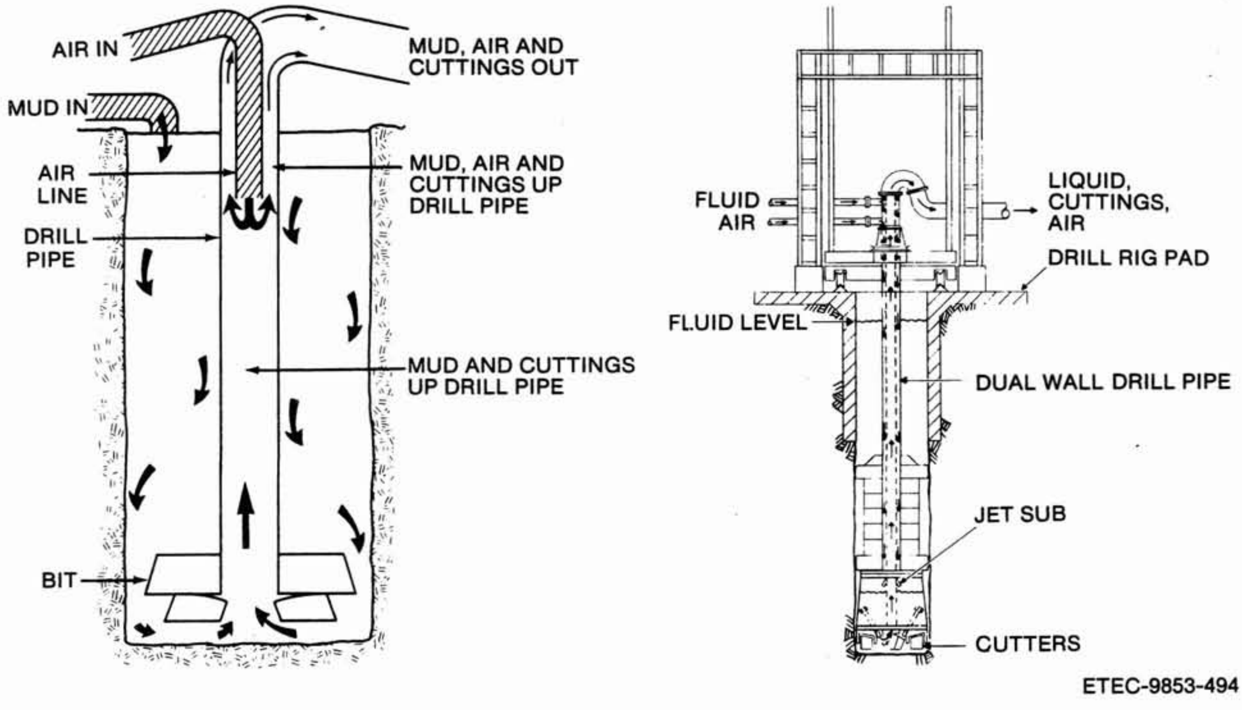

Figure 13. Single-Wall and Dual-Wall Air-Assisted Reverse Circulation

the bore hole is normally filled with drilling fluid. Compressed air is injected into the inside drill pipe. The air expands as it rises to the surface, reducing the hydrostatic fluid column contained within the drill pipe. Since the fluid column between the outside of the drill pipe and the wall of the bore hole does not contain entrained air, its greater density results in a differential pressure between the two fluid columns, which causes fluid and cuttings to flow from the bore hole into the drill pipe to return to the surface.

A typical surface layout of the ancillary equipment is shown in Figures 14 and 15. The layouts vary because the equipment is normally site-specific for each shaft project. The layout shown in Figure 15 is that for an Australian project by a Sante Fe Australian affiliate, the Australia Shaft Drilling Company. A 14-ft-diameter hole was drilled to a depth of 2460 ft through rock having a maximum compressive strength in excess of 50,000 psi. The maximum penetration rate was 25 ft/day.

Estimated drilling costs, using NTS costs as a basis for a 30-in.-diameter and a 10-ft-diameter CWP, are presented in Table 3.

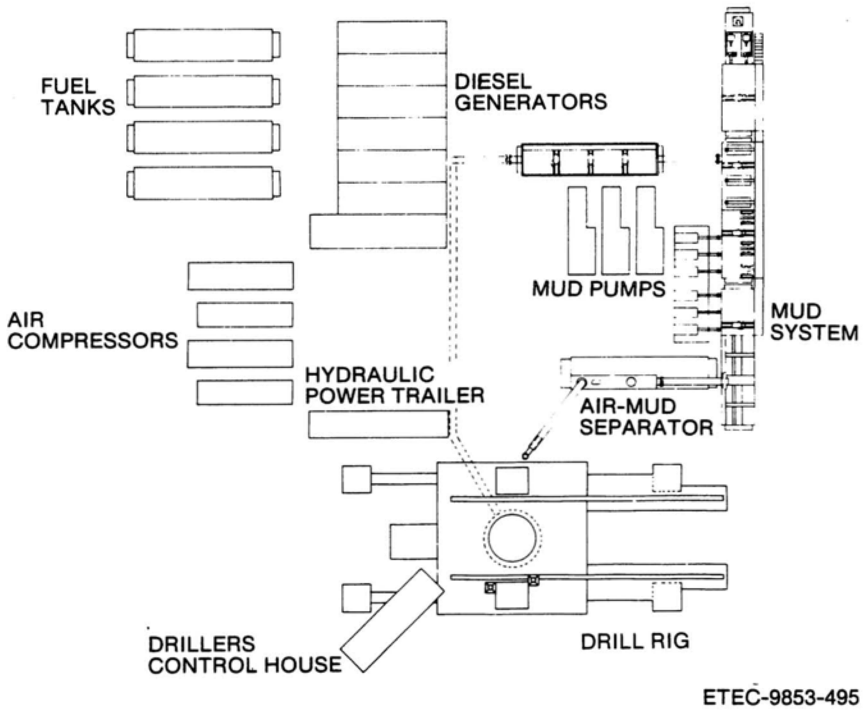

Figure 14. Shaft Drill Rig Site Layout

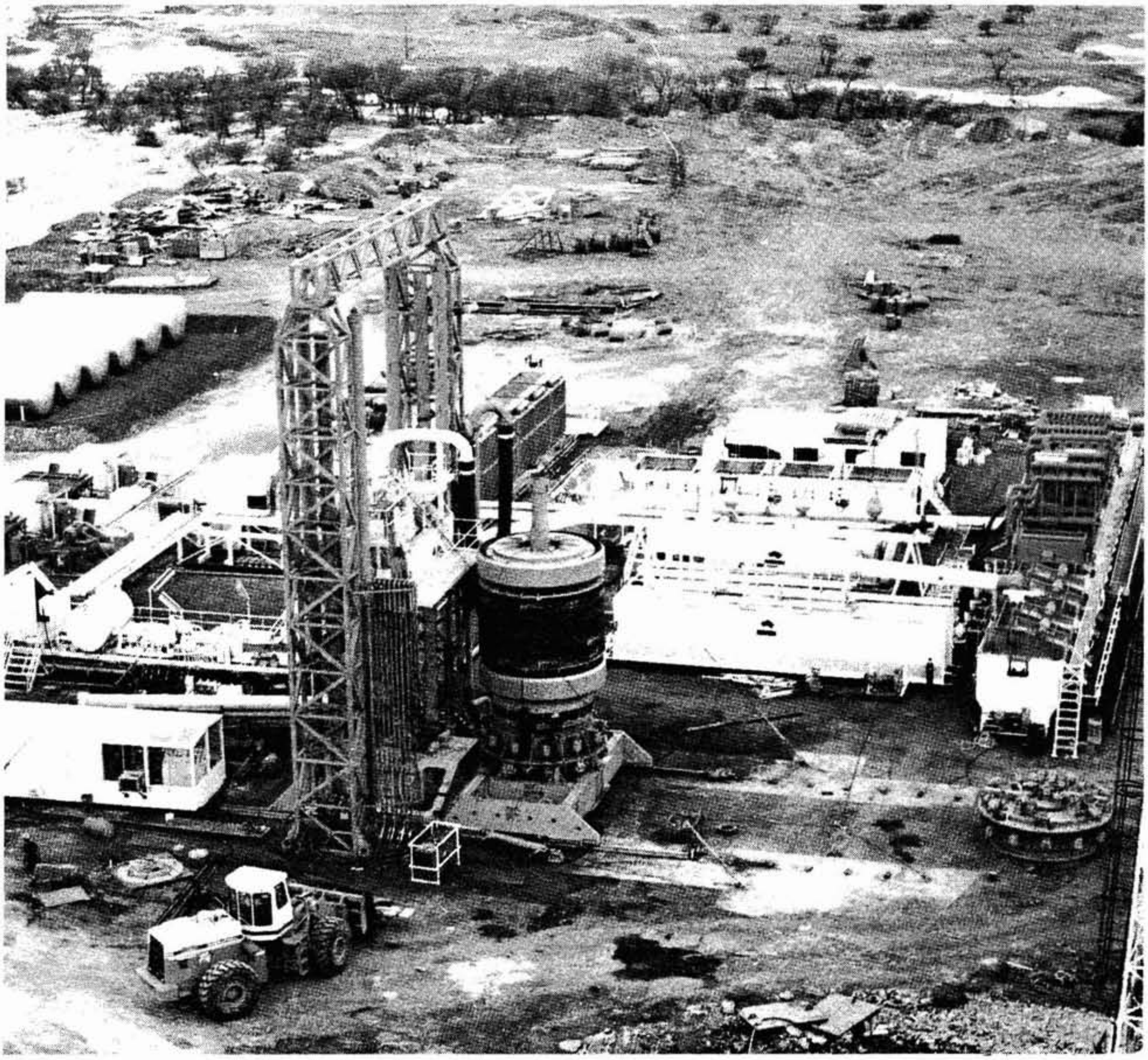

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Figure 15. Drilling Operation in Western Australia

TABLE 3

NTS ESTIMATED DRILLING COSTS FOR VERTICAL HOLE

	30-in. ID	10-ft ID
Site prep (300 by 300 ft)	$ 200,000	$ 200,000
Setup	$ 100,000	$ 200,000
Rig size	250 tons	1,000 tons
Drill rate	5 ft/h	1 ft/h
Number of days (3,000 ft)	25 days	125 days
Cost per day	$ 25,000[a]	$ 36,000
Casing (600 ft)	$ 100,000[a]	$ 313,000
Casing days	2	2
Total days	27	128
Drill rig subtotal	$ 675,000	$4,608,000
Cost at NTS subtotal	$1,075,000	$5,321,000
Shipping to Hawaii	$ 600,000[a]	$1,000,000[a]
Subtotal	$1,675,000	$6,321,000
Casing all the way	$ 500,000	$2,000,000
Total	$2,175,000	$8,321,000

[a]Estimated value

B. SLANT AND DIRECTIONAL DRILLING

Generally, even holes that are to be directionally drilled are begun vertically. It is possible, however, to begin the hole at an angle of 30° to 45° from vertical. Slant rigs, for example, have been used to drill directional holes by starting at an angle. Aside from the fact that the mast is slanted from the vertical and is modified somewhat from conventional rigs, most rig equipment is similar to that used on other rigs, and slant rigs operate much the same as do conventional rotary rigs. Slant rigs are used when it is necessary to drill a hole at an extreme angle from the vertical. The mast or derrick is tilted to cause the hole to deviate from the vertical at a shallower depth and with more ease.

The direction of the hole can be changed by several methods. The angle of the hole can be increased or decreased by adjusting drilling conditions, such as the weight on the bit or the speed of rotation, or by using special tools designed specifically to alter the direction of the hole. An understanding of the types of formations being drilled and their relationship to the earth's surface is important in choosing the tools and drilling conditions to use to drill a directional hole.

One modification of the conventional rotary drilling method is to use a downhole drilling motor. Conventional rigs are used, and all of the major equipment is the same as that used when rotating the bit with the drill pipe. Even the rotary table is used to turn the drill string slowly when drilling with the downhole motor. This prevents the pipe from sticking, but it does not provide power to the bit. Instead, the power to turn the bit is provided by the downhole motor pumping drilling fluid through the motor. The capacity of the rig mud pumps is, therefore, critical when drilling with a downhole motor. In effect, the motor power for drilling is supplied by these pumps instead of the rotary table.

Much of today's directional drilling is done with downhole drilling motors used in combination with a bent sub (Figure 16). The bent sub is a section of drill pipe manufactured with a slight angle that is installed in the drill string above the bit. The built-in angle of the sub exerts a side force on the bit and causes it to be deflected from the previous direction of the hole.

The drilling concept for OTEC applications is similar to the "extended reach" drilling operations in the oil industry. Because of the higher angles (from vertical), certain problems common to all directional drilling schemes are aggravated. For instance, the movement of the drill pipe and the resultant wear and friction are more pronounced. Dailey Directional Services, Inc., has developed a drilling program based on a catenary curve. Its theory is that the suspension of the drill string will form a catenary curve. When the drill string approaches a catenary curve, the string will move away from the

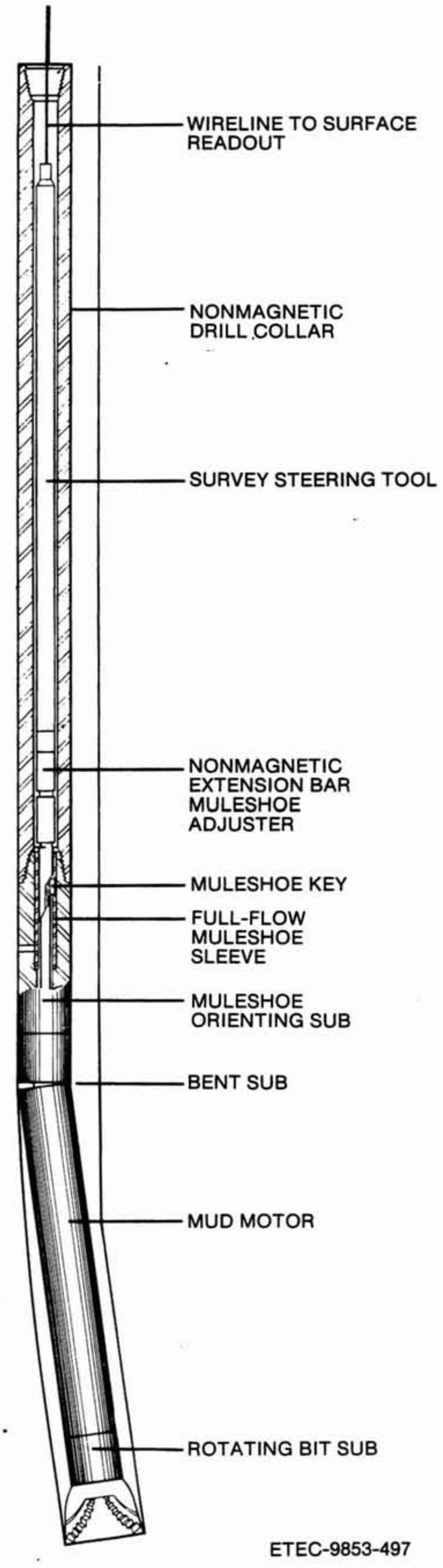

Figure 16. Bent Sub with Mud Motor

from the wall of the hole and tend to become suspended in the hole. This will reduce friction, thus allowing a greater application of weight and torque to the drill bit, which will increase the rate of penetration and reduce wear on the drill string.

The record for horizontal displacement by directional drilling was achieved by an oil well completed from an offshore platform in Australia's Bass Straight. This well reached a horizontal distance from the platform of 15,082 ft with a vertical depth of 7974 ft.[3] The trajectory was controlled and corrected by computer to avoid interference with existing wells. Aluminum drill pipe was used to drill much of the hole because its lower weight resulted in less drag on the low side of the hole and lower torque.

To date, directional holes have been limited to 26 in.[4] Although this size is inadequate for large-diameter OTEC applications, the directional hole can serve as a pilot hole. Several of the drill contractors suggested drilling a pilot hole and reaming in either a single pass or in several steps. One such cutter setup is shown in Figure 17. Although the figure shows only a single row of cutters, other cutters have in the past been added aft of the first to reduce the number of passes. The disadvantage of this method is that all cutters cut "gauge," where the highest cutter wear occurs, thus requiring more trips and higher cutter service and replacement costs. Figure 18 shows a tool that combines the drilling and underreaming job into one. Cutter arms for the reamer can be adjusted at the surface by using forced links, or the arms can be extended hydraulically during drilling. In harder formations, it may still be necessary to drill in stages. The hard-rock underreamer shown has a capability of 80-in.-diameter holes.

Robbins Company built a prototype shaft reaming machine that was used on the Chicago Water Storage project. This machine was specifically designed to enlarge an existing 6-ft-diameter vertical shaft to a diameter of 12 ft in relatively competent rock (Figure 19). The cutter head was powered by two 125-hp electric motors through gearbox assemblies meshed to a common ball gear. During the boring cycle, the rear shield gripper assembly held the unit

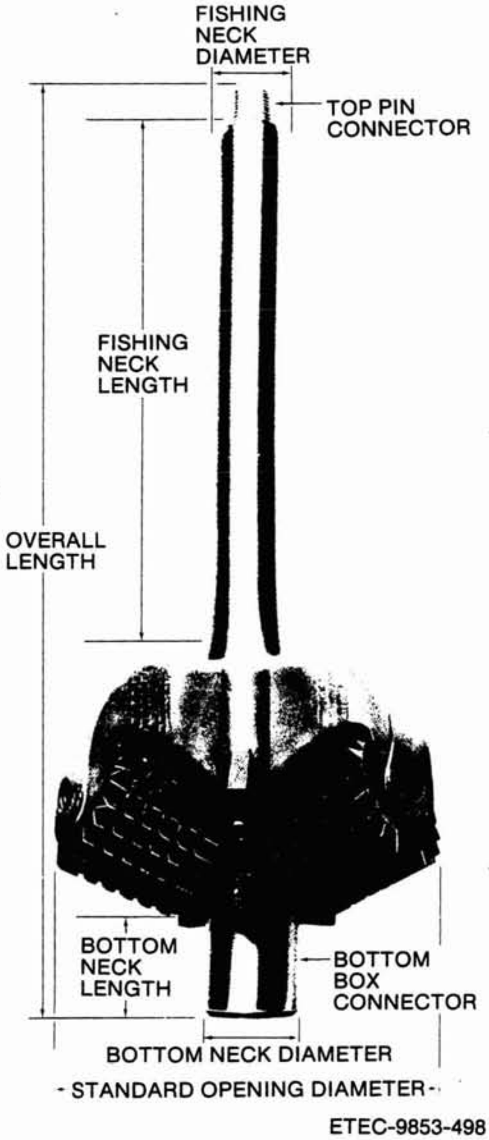

Figure 17. Drilco Large-Diameter Hole Opener

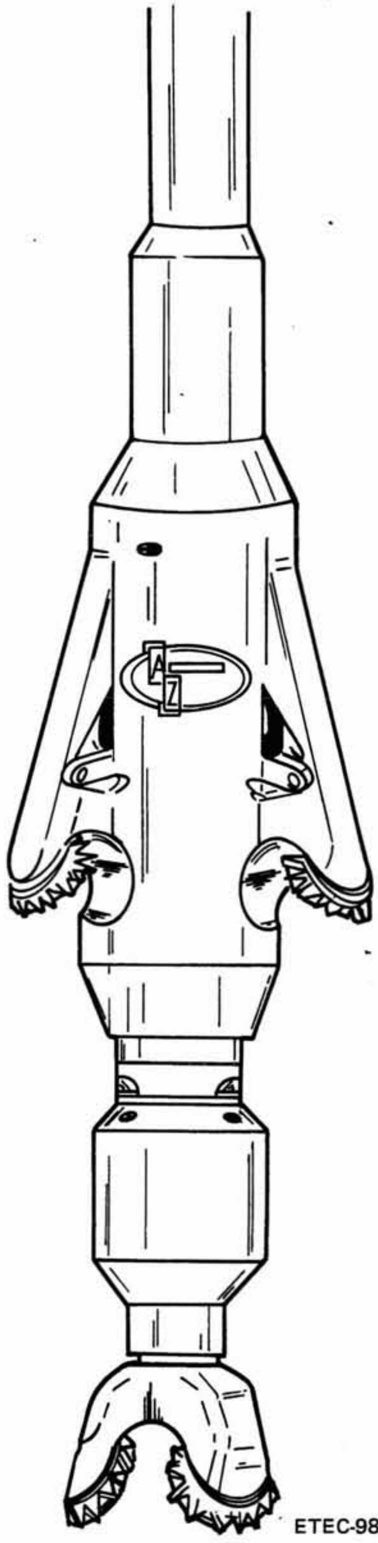

Figure 18. A-Z DUR Underreamer

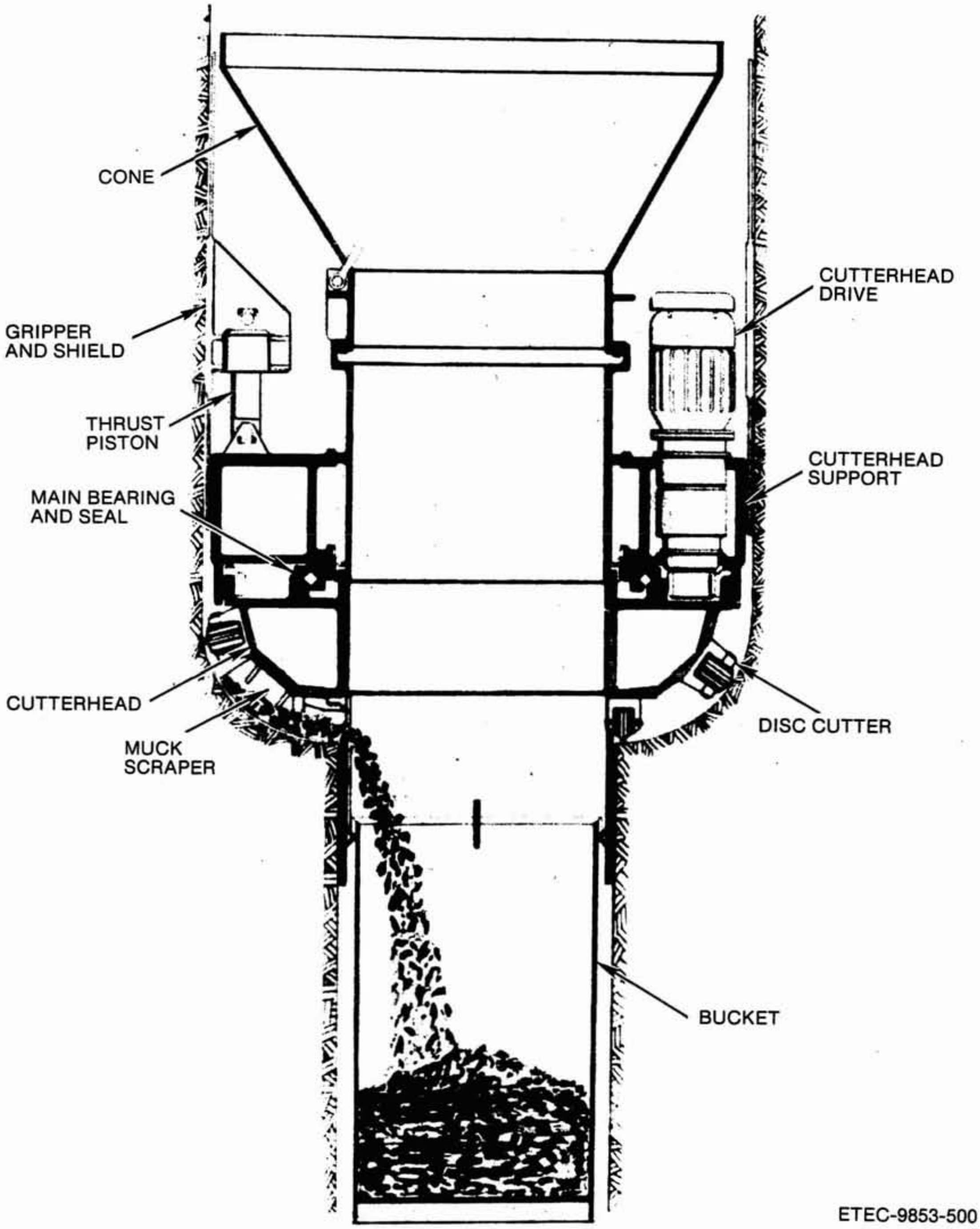

Figure 19. Robbins Shaft Reamer Model 1211-194--Operational Sketch

in the shaft while hydraulic cylinders thrust the cutter head into the hole. Torque and thrust forces were reacted through the gripper pads. At the end of the boring stroke, the machine would rest on the shaft bottom while the rear grippers or shield halves were released and pulled down by the retraction of the hydraulic cylinders. During the excavation of the shaft, the best performance attained was an advance of 55 ft in 9.5 h, which included 60 regrip cycles. This machine was built for about $250,000.[5]

The Robbins machine is not that different from the "Flexidrill" specialty rig. This rig used flexible drilling hose as a drill string instead of rigid steel pipe. The flexible hose contained electrical conductors that provided power to drive a motor at the bottom of the drill string to rotate the bit. Adapting features of the two systems could well result in a fully remote underwater boring machine.

Large-shaft applications have primarily been vertical shafts for testing nuclear devices at NTS, disposing of nuclear waste at Hanford, ventilating mine shafts, and excavating foundations for offshore oil platforms. However, there has never been a requirement to drill large holes at angles approaching horizontal. Major problem areas with such an operation are the loss of weight on the bit and of the directional control of the bit. Because it is impossible to allow the weight of the mandrel to apply the force on the bit, the drill string must be loaded (pushed) from the rig. The stabilizers that must be added to center the string there (because of friction losses) reduce available torque to the bit. In addition, the stabilizers complicate the handling of the drill string each time a "trip" is made (removal of the bit for cutter service). An alternative approach is to use nonrotating stabilizers on the mandrel after modifying them to not only center the bit but also to apply forward thrust.

Development is required in the directional drilling of large-diameter holes. The absence of the requirement for men in the hole for a site with fissures and fractures makes slant drilling technology a worthwhile pursuit. Costs are expected to be higher than for vertical holes because of (1) the longer shaft for a given depth and (2) the complexity of additional stabilizers and control mechanisms on the bit.

C. TUNNEL BORING

An alternative to directional shallow-angle drilling is tunnel boring. As with drilling, the mechanically bored tunnel yields a smooth wall, which is easily lined. In most machines, a full circular cutting head is employed. The cutting tools are mounted in an arrangement suitable to excavate a tunnel of the required diameter when the head is rotated against the working face. A typical rock boring machine is shown in Figure 20, together with the ancillary equipment necessary in an actual tunneling operation.

The machine body is mounted immediately behind the cutting head and remains stationary while the cutting head excavates. The body incorporates a mechanism to maintain its stationary position during excavation and to move itself and the cutting head forward to continue the excavation. The machine body also contains the mechanical equipment to provide the necessary thrust and torque transmitted through the cutting head to the cutters.

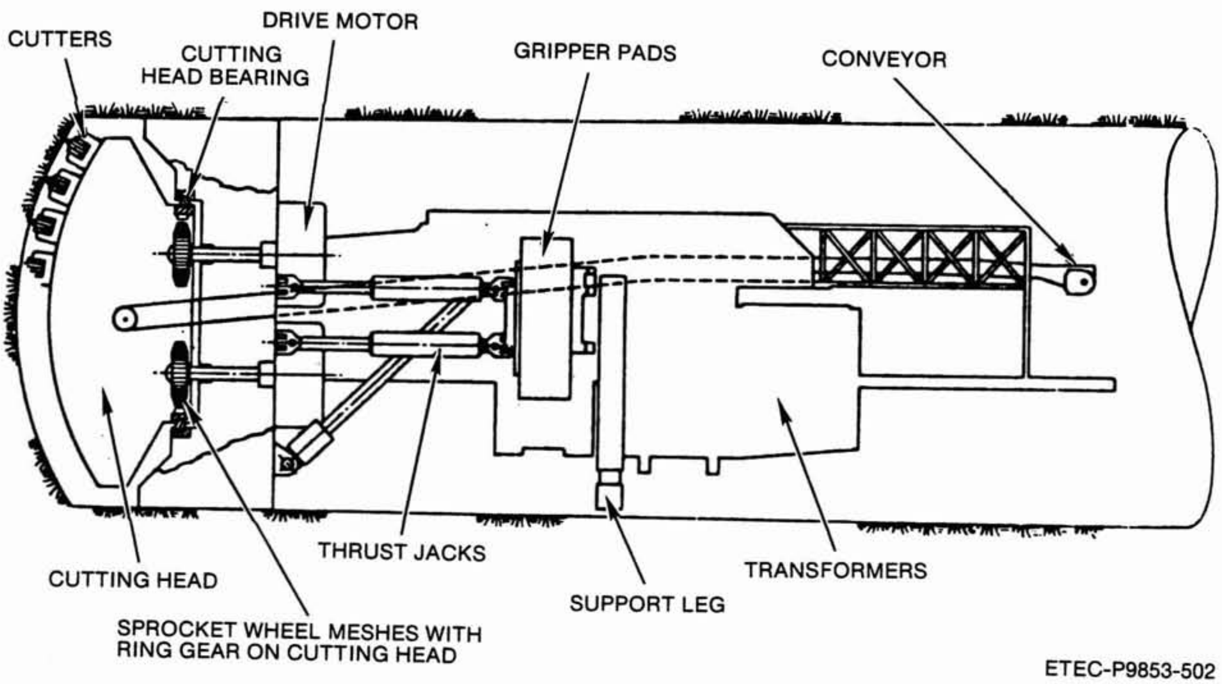

Figure 20. Rock Tunneling Machine and Ancillary Equipment

The characteristics of tunneling machines are determined by the kind of formation in which they are designed to operate. The material at Keahole Point is expected to be hard rock (basalt) with a compressive strength of ≥50,000 psi. However, because of the crystalline structure of the lava, it is expected to be drillable. Several different types of cutters have been developed for working most efficiently in various formations (Figure 21). With the exception of the disc cutter, the cutters are similar to the large hole cutters described earlier. The single disc cutter consists of a disc-shaped base mounted on a roller bearing with a replaceable cutting edge of hardened steel around the disc. This cutter is commonly used in medium hard rock. Disc cutters are also available in single- and double-row carbide for extremely hard rock.

The Robbins Company of Seattle built one of the largest tunneling machines yet used with a diameter of 38 ft 8 in. for driving the combined diversion and power tunnels for Mangla Dam in Pakistan (Table 4). This machine was later modified for driving two tunnels under the Mersey River in England through wet sandstone crossed by several faults. The diameter was reduced to 33 ft 11 in. While the first tunnel was being driven, the 16-ft-diameter main bearing was replaced. The bearing probably failed because of the damp environment. The motors and hydraulic equipment were relocated in waterproof housings for protection against the large inflow of water.[6]

Wirth Corporation in Germany bored a 34.3-ft-diameter road tunnel in Switzerland. The tunnel was bored in three steps:

- An 11-ft-diameter pilot was driven by one machine for the entire length of the tunnel.
- Another machine, with cutting heads in the form of concave annular rings, then enlarged it to 22 ft in diameter.
- Finally, a similar cutter head increased the excavation to its full size.[4]

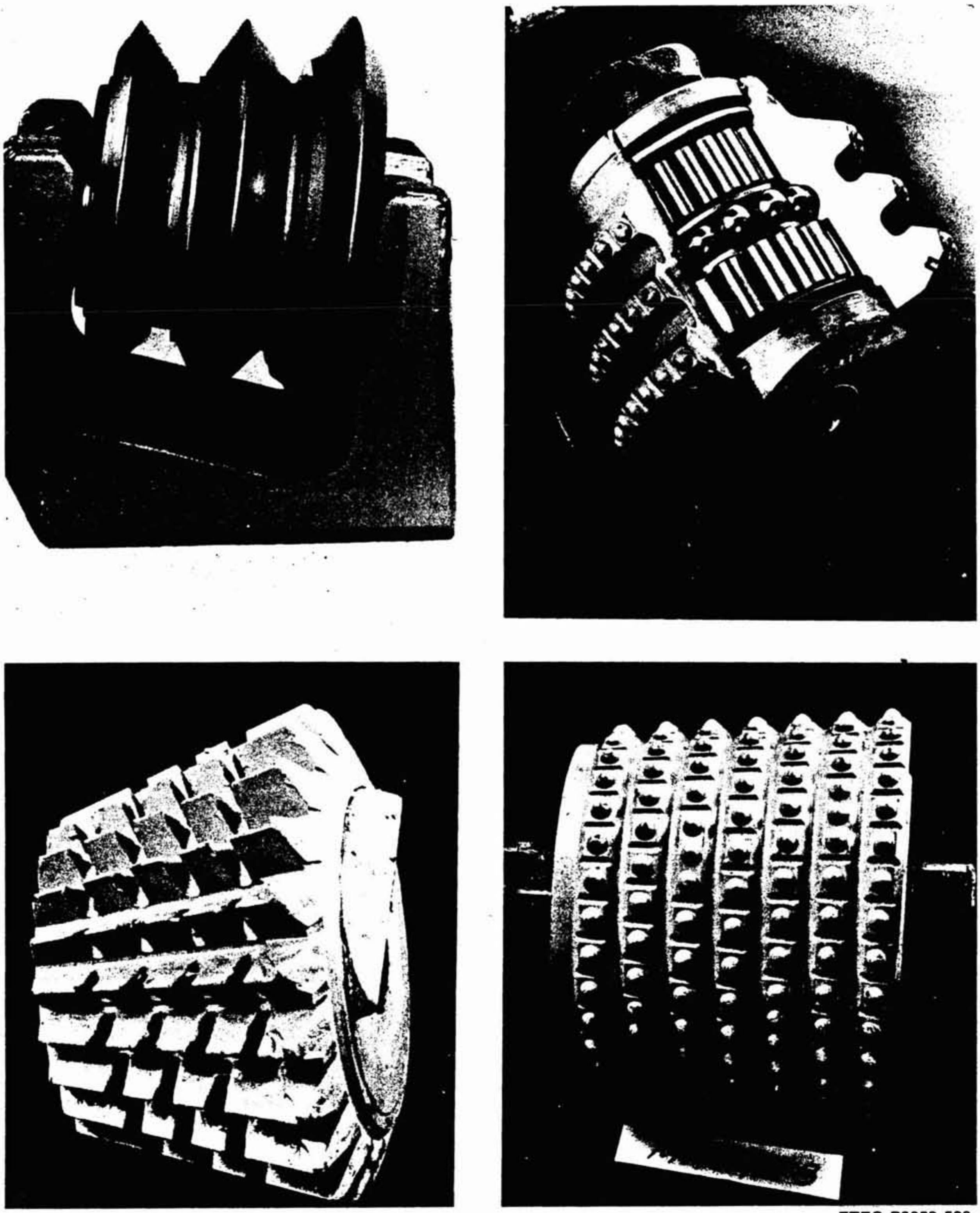

Figure 21. Type of Rock Cutters

TABLE 4

TYPICAL CHARACTERISTICS OF ROTARY FULL-FACE ROCK TUNNELING MACHINES

Manufacturer	Project Location	Machine Diameter (ft-in.)	Thrust (lb)	Cutting Head Torque (lb•ft)	Cutting Head Horsepower
Robbins	Mangla Dam, Pakistan Mersey Road Tunnels, England	36-8 33-11[a]	600,000	5,250,000	1,000
Robbins	Oso Tunnel, Colorado	10-2	372,000	175,000	300
Jarva	Bay Area Rapid Transit, California	20-0	2,200,000	660,000	825
Ingersoll-Rand	Port Huron Tunnel, Michigan	18-4	1,500,000	500,000	750
Hughes	Navajo Irrigation Project, New Mexico	19-10	900,000	--	1,000
Dresser	Navajo Irrigation Project, New Mexico	20-6	1,080,000	703,000	720

[a]Same machine as for Mangla Dam, modified for smaller diameter

Atlas Copco machines worked on the Seikan tunnel in Japan, an undersea railway line under the 13.5-mile-wide strait between the islands of Honshu and Hokkaido. One end passed through consolidated volcanic ash with a compressive strength of 4400 psi; at the other end, the rock was andesite containing water-laden faults.[6]

The use of tunneling machines has been extended to steeply sloping tunnels. In separate hydroelectric projects in Switzerland, tunnels were excavated at angles of 33° and 42°. The tunnels were driven upward from the lower end of a vertical shaft. The sloping tunnel was found to have a distinct advantage over a horizontal tunnel for the removal of cuttings from the face.[7]

One concern about a tunnel in the Keahole Point area is the presence of water resulting from permeability and/or fissures and lava tubes. Tunnel boring machines are normally manned: crews operate the machines and perform maintenance in the tunnels. Mr. Friant of Robbins Company compared the tunneling machines to small, moving machine shops. The crew for a large tunnel boring machine consists of 12 operators in the tunnel with an additional 6 support personnel at the surface. However, the technology for a fully remote tunneling machine appears to exist. The Robbins shaft reamer (Figure 19), although operated in a vertical application, is essentially a forerunner of the remote tunneling machine. Another boring machine, again operated in a vertical attitude, was designed by Hughes Tool Company (Figure 22). The machine was used for boring mine shafts of varying depths. The driveshaft was rotated by hydraulic motors. The machine was prevented from rotating in the bore by two horizontally placed anchor jacks that thrust against the walls of the shaft. A vertical jack below the horizontal jacks provided downward thrust on the core barrel and the cutters. The machine followed a pilot hole, which also served as a conduit for removing the cuttings.[6] Although this machine was manned, it appears that it could fairly easily be adapted to remote operation.

Robbins felt that a manned 14-ft-diameter machine could be built for about the same cost as a 10-ft-diameter machine. A 14-ft-diameter horizontal tunnel was built in the Lake Michigan area. The tunnel was 22,000 ft long and cost $17,000,000, or about $800/ft.[5] ETEC prepared an estimate for a 14-ft-diameter, 5000-ft-long tunnel. The estimate, shown in Table 5, is for a manned tunneling operation.

The development of an unmanned, remotely operated, underwater tunnel boring machine is possible. Robbins estimated that a large-diameter (14-ft) machine could probably be built for about $5,000,000 plus $5,000,000 for development. However, as this would be a prototype, another $5,000,000 would most likely have to be invested to complete a production model. Such a machine could probably tunnel at a rate of 50 ft/day, depending, of course, on the geologic formation of the site.

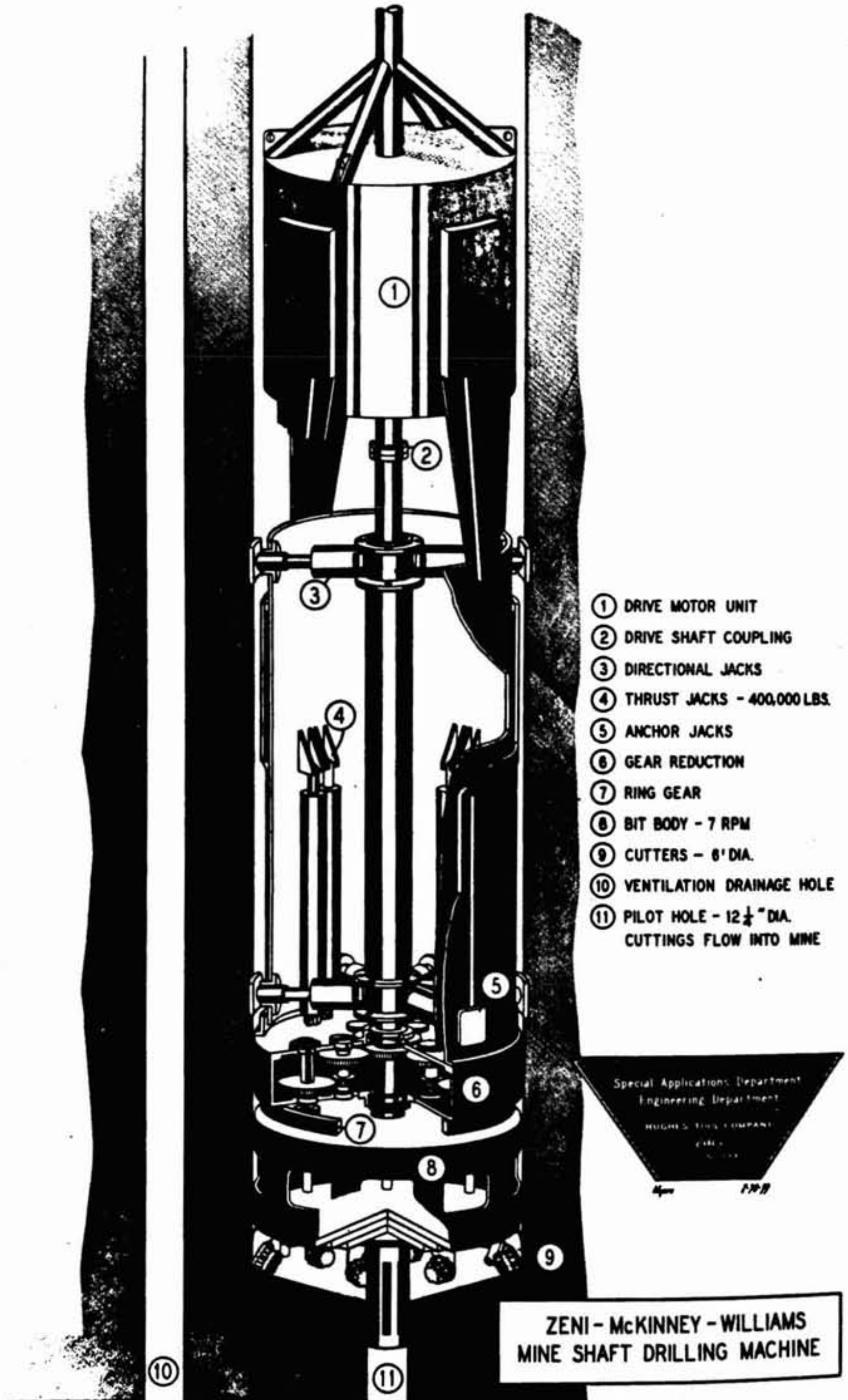

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Figure 22. Hughes Mine Shaft Drilling Machine

TABLE 5

ROM COST ESTIMATE FOR
14-ft-DIAMETER TUNNEL

Item	Cost ($$10^6$)
Engineering	1.0
Staging	0.5
Shipping	0.5
Machine	7.0
Crew[a]	2.0
Lining	2.0
Seaport	1.0
Completion	1.0
Total	15.0

[a](20 men) (4 shifts/day) (100 days) ($250/man shift) = $2,000,000

This is illustrated in Figure 23, which represents the costs of tunneling 10- and 25-ft-diameter shafts in basaltic lava (Keahole Point, Hawaii) and carbonate sediment (Punta Tuna, Puerto Rico). Tunneling rates vary from 25 to 60 ft/day, respectively. For comparison, costs for 10- and 25-ft-diameter above-bottom conduits are superimposed on the figure. The results indicate that for conduits greater than 10 ft in diameter, tunneling may provide a viable alternative for meeting the OTEC long-term cost goals.

D. CASING

Once the shaft has been drilled to the desired depth, several options are available to provide a permanent liner. Since the shaft is bored by rotating equipment, a smooth wall is created. If cracks and fissures are present in the surrounding strata, there may be communication between the shaft and the ocean. In that situation, a casing should be installed to a depth sufficient

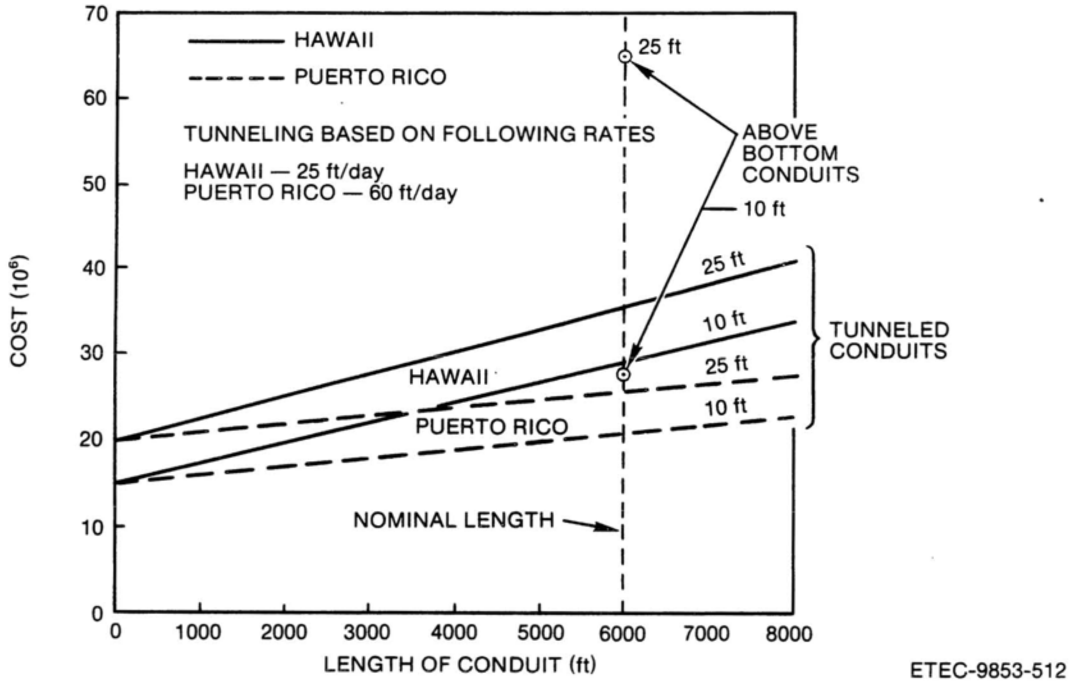

Figure 23. Costs of 10- and 25-ft-Diameter CWPs

to ensure that the temperature of the water entering the shaft will be sufficiently low. Since the shaft will be full of water, the casing does not have to withstand hydrostatic collapse forces. The lower part of the shaft will be left unlined or use a slotted casing to allow water to enter the shaft.

Most of the shaft liners installed in large shafts have been constructed of steel. Sections of flat steel plate, ranging in thickness from 3/8 in. to over 2 in., are rolled together into a cylindrical "can." Stiffener rings, which are typically solid-steel bars of varying dimensions, are then welded at an engineered spacing around the outside circumference of the cylindrical pipe segments to increase their resistance to collapse from external compressive forces. This fabrication work is usually performed in a shop, and then either 20- or 40-ft-long segments of the liner are trucked to the shaft location. To reduce the time required to install the complete liner system, liner segments are sometimes welded together into 80-ft lengths at the job site during shaft drilling operations.

Either a large crane or the drill rig itself can be used to lower the liner into place. NTS estimates that 240 ft of 10-ft-diameter, 5/8-in.-thick casing can be installed in 24 h.[2] Tunneling machines are equipped with hydraulic actuators that install the lining without interruption of the cutting process. A shield supports the liner segments until the final segments are installed and thus provide the interlocking support that prevents collapse.

For larger-diameter shafts, the cost of fabricating a steel liner system that is capable of withstanding hydrostatic collapse forces through its entire depth can be very high. As an alternative to the fabricated steel liner, a system has been developed to install stacked-in-place precast concrete liner segments (Figure 24). Each segment would typically be 10 to 15 ft high and have a wall thickness of 10 to 24 in. A 14-ft-ID liner segment having a 2-ft wall thickness would weigh about 75 tons. During shaft drilling operations, the concrete sections can be cast and cured on the job site, using a mobile

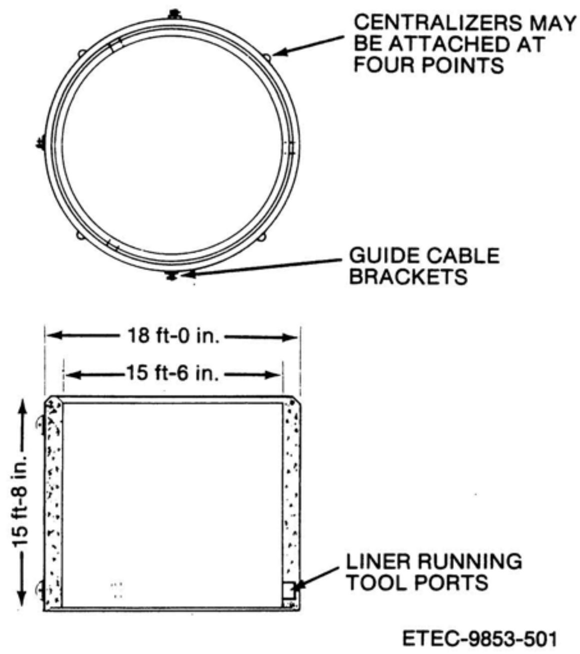

Figure 24. Typical Precast Concrete Liner Segment

batch plant to produce the concrete mixture. Geological and hydrological conditions present at a given shaft site may require the use of extremely high-strength concrete liner segments. Concrete having a compressive strength of 12,000 psi can readily be produced by using polymer or latex-type additives in the concrete mix. Vibrators are used on the steel inner and outer forms to ensure that the concrete is properly compacted, with no air pocket voids present. A cage of reinforcing steel is cast within each segment to prevent cracks caused by shrinkage or handling. Three steel ports are cast into the lower portion of each liner segment to mate with the retractable rams of the liner running tool during the installation phase.

If, however, the rock is competent and little or no permeability occurs, the hole can be lined in the area of water in-leakage, the shaft pumped dry, and a decision made as to whether or not to tunnel. Even if there is no significant influx of water, the shaft would require lining, perhaps shotcrete, to maintain the hole and provide for the safety of personnel.

V. DRILLING AND/OR TUNNELING CONCEPTS

ETEC has identified five different concepts for drilling and/or tunneling a cold water conduit for OTEC applications:

- A vertical shaft with communication to the ocean via fissures, lava tubes, or permeable lava
- A constant-angle slant-drilled shaft at an angle of approximately 20° from horizontal
- A shaft drilled along a curved path starting at a 45° angle and approaching the seaport horizontally or at an upward angle
- A near-horizontal tunnel from the bottom of a vertical shaft 2300 ft deep
- A tunnel at an angle of approximately 20° from horizontal; this concept differs from the slant-drilled concept in the method of producing the hole.

Since each concept is a function of the geologic, hydrologic, and geomechanical properties of the area, a geologic model was first developed for Keahole Point (Figure 25).[8] The preliminary model identified five major rock and sediment types: (1) pillow basalts, (2) pyroclastic debris, (3) basalt lava flows, (4) basaltic dike complexes, and (5) carbonate sediments or limestone.

Pillow lavas and pillow fragments of tholeiitic basalt make up the bulk of the island mass. These pillow basalts erupted in intermediate to deep water and probably had a fairly high initial permeability. This high initial permeability quite likely has been reduced by compaction and chemical alteration.

Pyroclastic debris mantels the older pillow basalts and represents a transition from the deep submarine pillow basalts to subaerial flows. These pyroclastics erupted in shallower water as the submarine volcano built toward

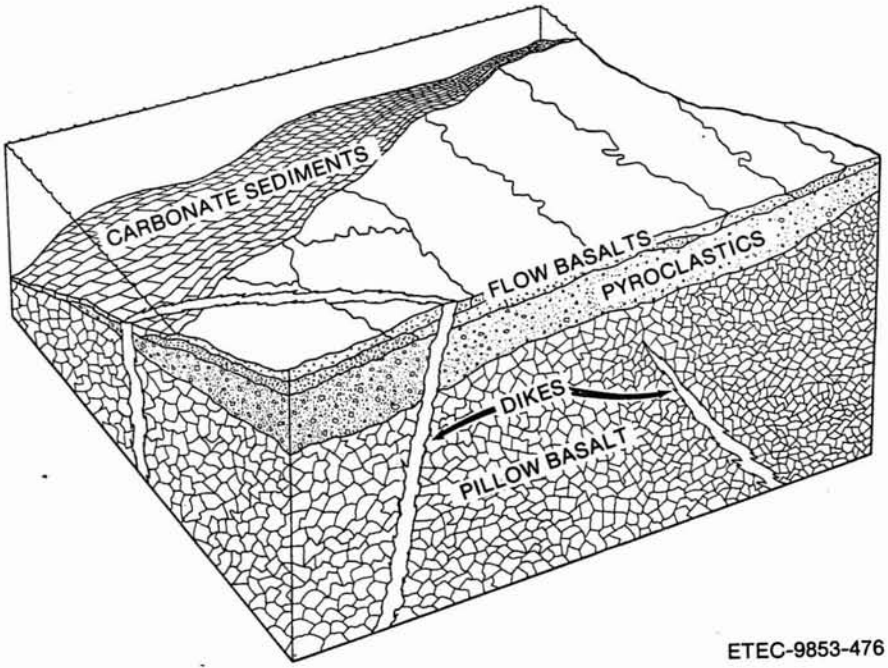

Figure 25. Preliminary Geologic Model of Keahole Point

the surface of the sea. Because of the reduced pressure, the hot lava contacting the sea water resulted in steam explosions, which produced the pyroclastic debris and distributed it over the pillow basalts. No information on the thickness of this unit for the Keahole Point area is available, but a well on the eastern side of the island encountered about 538 ft of transition rocks. Because the prevailing winds are from the east, it is likely that this unit will be somewhat thicker on the western coast of the island. The high initial permeability of this unit has probably been reduced by compaction and chemical alteration.

The subaerial basalt (and minor amounts of other lavas such as trachyte) make up the surface of the shield volcanos. The shields are built of many very fluid lava flows. The thickness of these flows in the Keahole area is unknown, but drilling on the eastern side of the island has revealed a cumulative thickness of about 1850 ft. Also revealed by drilling on the east side is the fact that at least 1000 ft of subsidence has occurred, thus carrying some of the subaerial flows below sea level. The Keahole model indicates this subsidence by showing some of the subaerial flows terminating below sea level.

The dikes are dense basalts that intruded into existing country rock, possibly along preexisting fractures. The permeability of these rocks is expected to be low. (They often act as barriers to ground water flow.)

Carbonate sediment mantles the shallow, submarine portion of the island. This material is of less importance, in terms of mass relative to the other rock types, but may be important with respect to its effect on any drilling or tunneling operation just below the surface (e.g., if tunneling is used for the warm water pipe).

A. DRILLING A VERTICAL SHAFT

If communication to the ocean exists at depth (through pores, lava tubes, or fissures), then the construction of a vertical shaft may be all that is required to fulfill a cold water supply requirement. This is illustrated in Figure 26. During the drilling process, the hole would have to be logged and possibly tested to determine the influx of ocean water at various levels. Casing will have to be installed to prevent warmer water at shallow depths from entering the shaft (e.g., casing to a depth of 2000 ft, with either slotted casing or no casing to 3000 ft).

B. DRILLING AT A FIXED ANGLE FROM VERTICAL (Approximately 70°)

If the influx of cold water into a vertical shaft is insufficient, the shaft must be drilled until the ocean bottom is penetrated below 2000 ft. There is the possibility that a layer of coral exists between the various lava flows or that lava tubes exist that follow the flows to sufficient depths. An attempt could then be made to follow these flows or tubes. However, until a careful survey has been made, it must be assumed that the hole must be drilled through primarily lava formations with possible voids and fissures. This is illustrated in Figure 27.

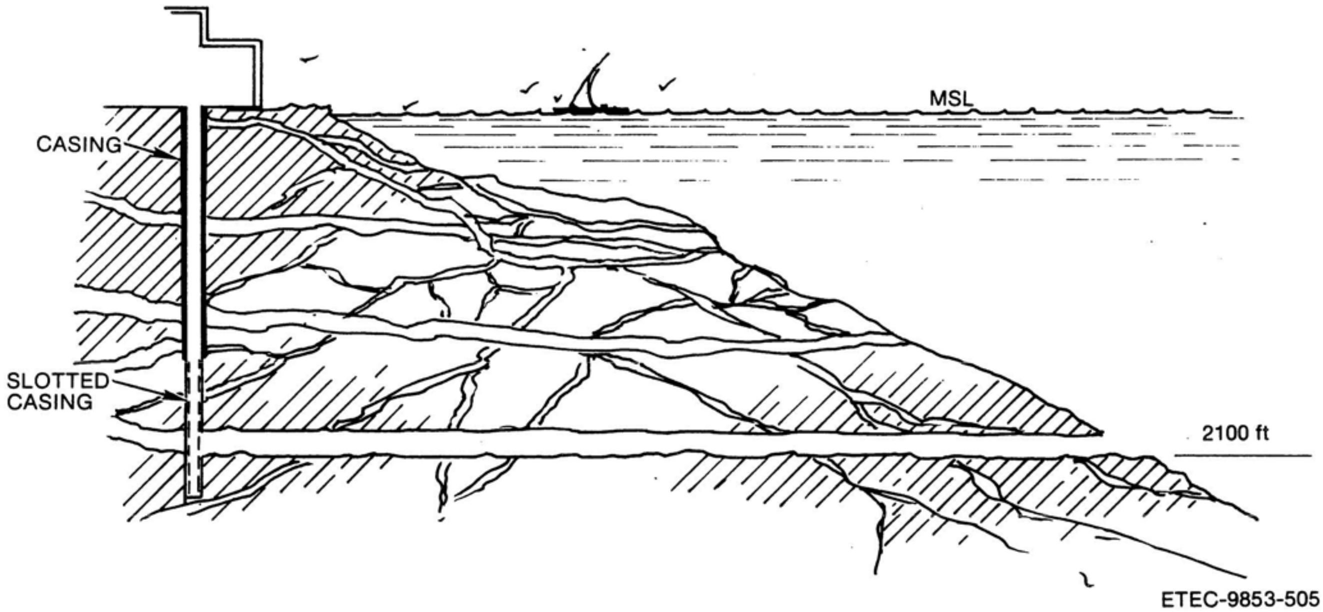

Figure 26. Vertical Shaft with Communication to Ocean

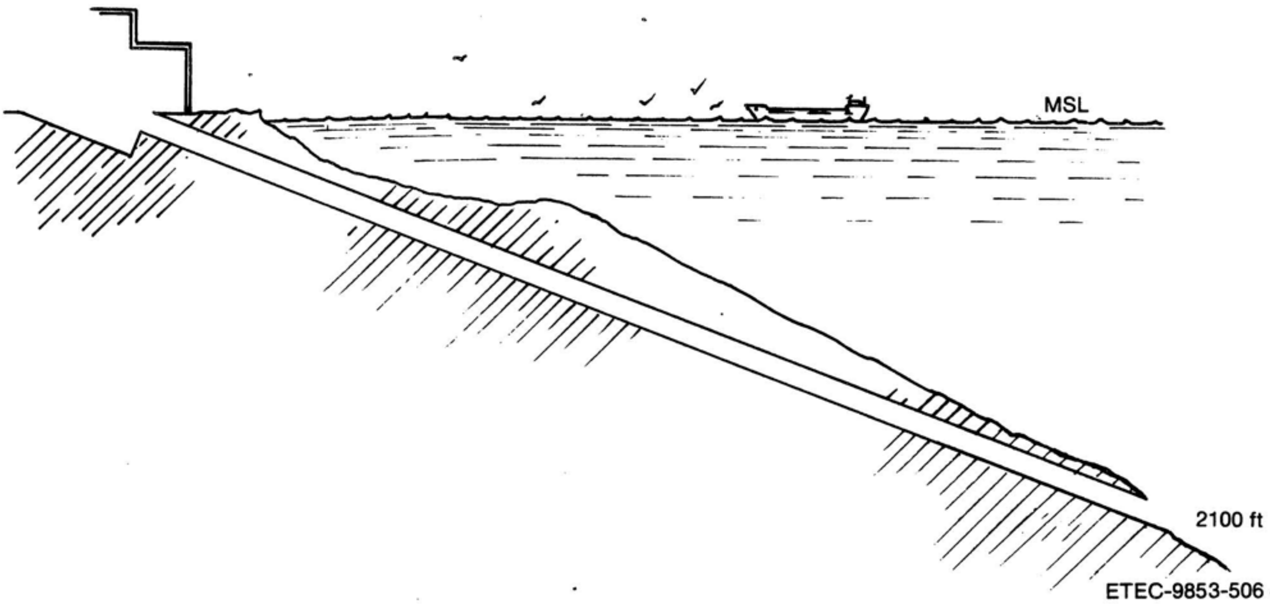

Figure 27. Drilling at a Fixed Angle from Vertical

C. DRILLING ALONG A CURVED PATH

This method is basically a variation of the second method and may be a real possibility if the catenary trajectory can be designed to minimize loading and torque requirements. Drilling contractors (e.g., Santa Fe) consulted thought it feasible to install casing for a 10-ft-diameter pipe so long as angles increased at less than 1.5°/100 ft of depth. This concept is illustrated in Figure 28.

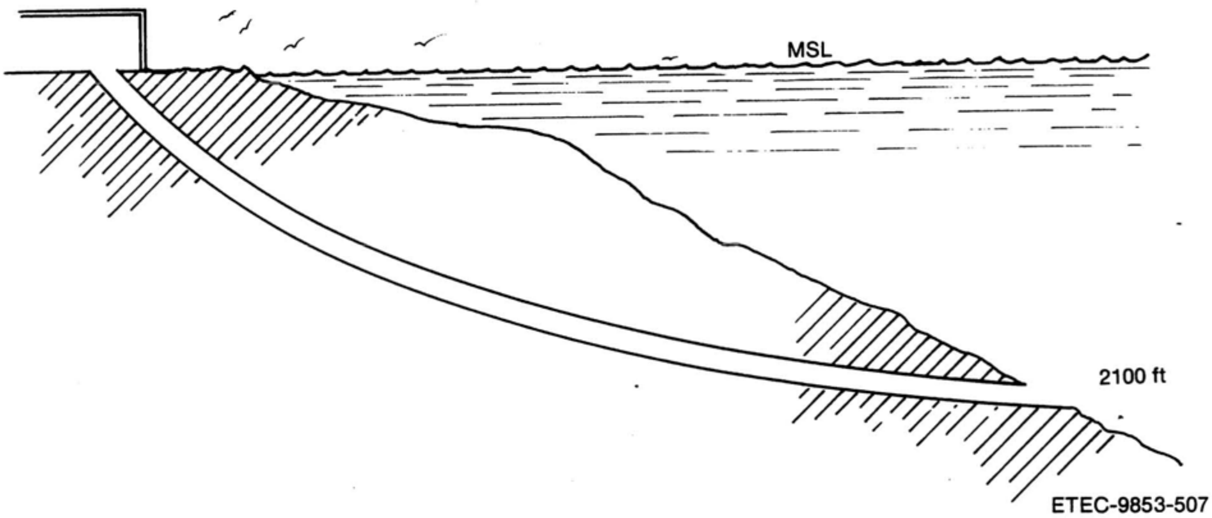

Figure 28. Drilling Along a Curved Path

D. TUNNELING FROM A VERTICAL SHAFT

This method, preferred by some of the drilling/tunneling industry experts contacted, is similar to the approach proposed by Rockwell International Hanford personnel for the Basalt Waste Isolation Project. The success of this approach is highly dependent on a "dry" hole. The vertical shaft would have to be cased, as necessary, to overcome any influx of ocean water. From the bottom of the shaft, a tunnel would be bored until the ocean bottom is penetrated. The tunnel would slope up at a slight angle (approximately 3°). With the exception of the final penetration, the tunnel boring machine would be manned. The machine is also capable of installing casing (either concrete or steel) with little delay in the boring operation.

As the ocean bottom is approached, a collection basin would be dug into which the debris would fall as the final plug is blown by explosives to create the opening to the ocean (seaport). An alternative to blasting would be to drill from a drill ship. This concept is shown in Figure 29.

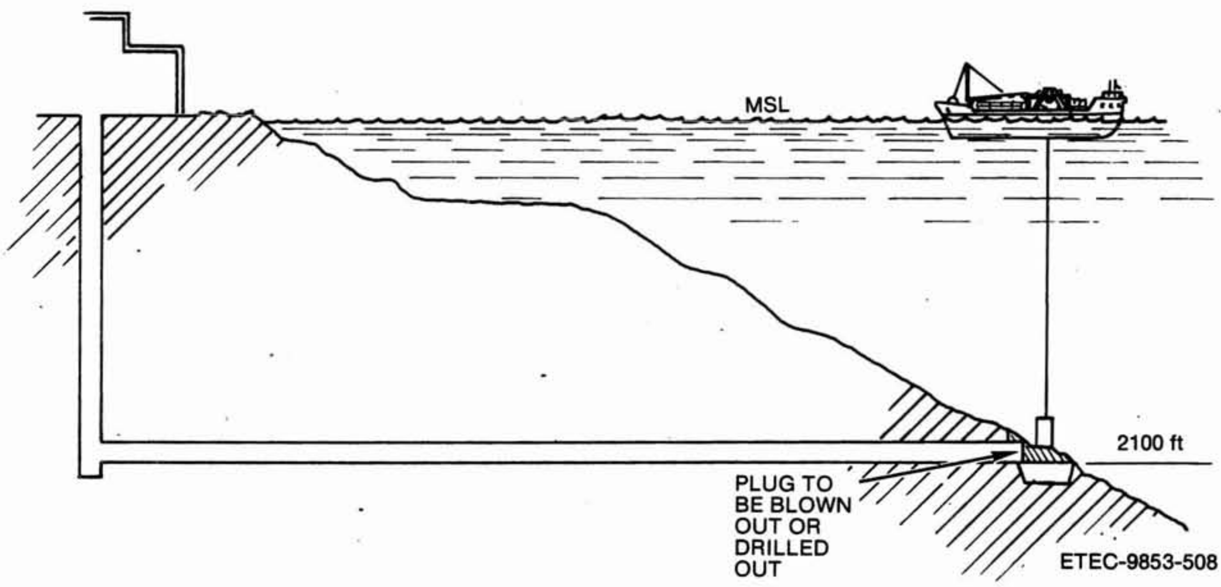

Figure 29. Tunneling From a Drilled Shaft

E. TUNNELING FROM THE SURFACE AT A 20° ANGLE FROM HORIZONTAL

This approach could be used if the path of the tunnel passes through competent rock with limited influx of seawater. An alternative approach would be to develop a remotely operated underwater mining machine. Although no such machine currently exists, it may be possible to combine certain drilling and tunneling technology to develop such a machine. Robbins Company has built a remotely operated drilling reamer that might be adapted to a tunneling machine to provide the desired capability.

In competent rock, no liner would be required. But in highly permeable rock or if large fissures or lava tubes exist, lining would be required. This is illustrated in Figure 30.

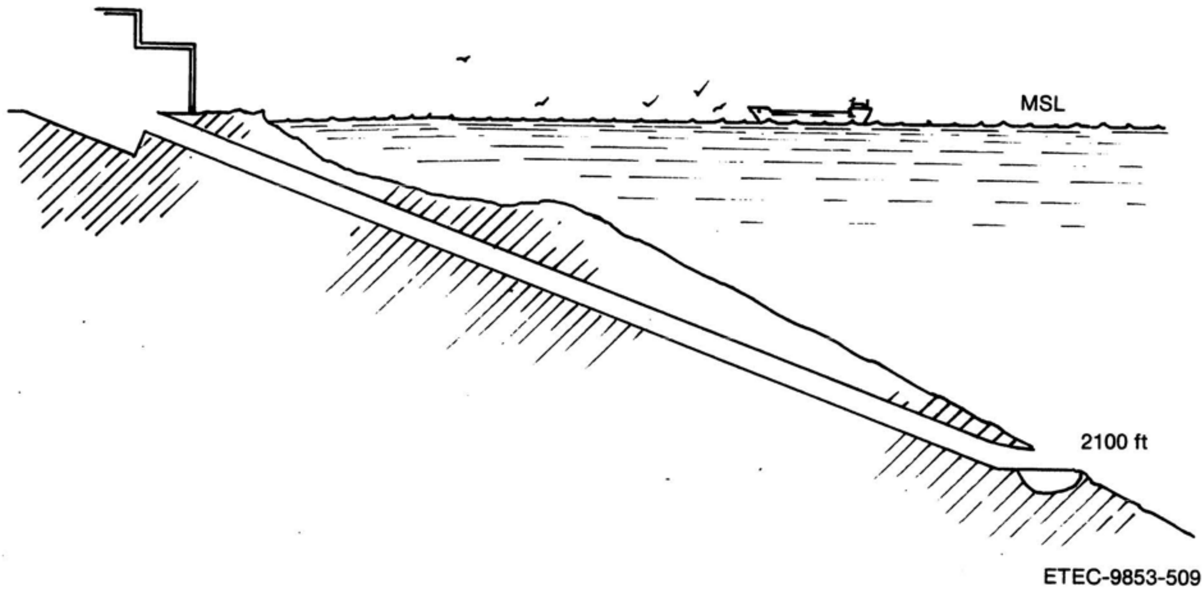

Figure 30. Tunneling From the Surface at a 20° Angle

F. COMBINATIONS OF TUNNELING AND CONVENTIONAL PIPING TECHNIQUES

One possible combination is to drill or tunnel a hole to an intermediate depth (600 to 1000 ft) and then to insert a pipe of nearly neutral buoyancy through the hole that, when it exits the hole, forms a catenary to the desired depth (greater than 2000 ft), as shown in Figure 31. The catenary eliminates the need to know the bottom in detail.

The tunnel eliminates the need for trenching and backfilling in the shallow zone. As pipe diameters get larger, dynamic loads increase rapidly, and satisfactory deployment and anchoring become increasingly difficult for surface-deployed pipes. Another use of a tunnel would be as a housing for several pipes (e.g., the cold, warm, and mixed effluent pipes) in the shallow zone.

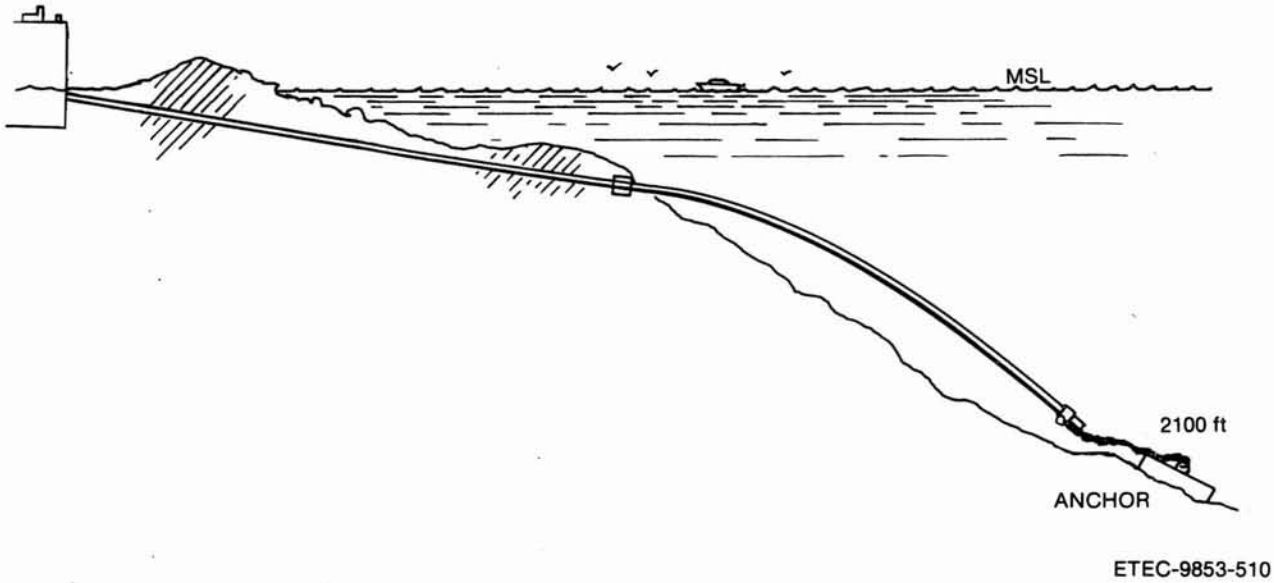

Figure 31. Drilled or Tunneled Shaft in Combination With a Buoyant Catenary

G. MIXED EFFLUENT DISCHARGE

The lava has been found to be very permeable from the surface to a depth of 600 ft, a feature that has resulted in the widespread use of injection wells. This feature makes the use of an injection well an immediate viable option for the disposing of the mixed water effluent.

Each concept is based on several assumptions about the site (e.g., geology and hydrology). At the surface, the lava is very porous and highly permeable. It is expected that communication to the ocean exists. However, it is not known whether this communication exists at the depth required for cold water collection (deeper than 2000 ft). Ultimately, the approach chosen and the resultant design of the shaft (whether drilled or tunneled) will depend on the geologic characteristics, hydrologic properties, and geomechanics characterization of the lava deposits at Keahole Point.

VI. CONCLUSIONS AND RECOMMENDATIONS

As bottom-mounted CWPs become larger, the costs increase exponentially, making it impossible to meet the long-range OTEC cost goals while using conventional technology. Tunneling and/or drilling offers a viable alternative for providing water conduits that are capable of achieving the long-range cost goals. For sizes greater than 10 ft in diameter, tunnels or large-diameter shafts become cost effective.

The shafts need not be limited to CWPs only. As shown in Figure 23, once a machine has been developed, operating cost represents a relatively small percentage of the overall cost. A machine could, therefore, be developed for a project and be used for cold and warm water conduits as well as mixed disposal.

For warm water pipes, the shaft would be located just below the seafloor, where the possibility exists on the island of Hawaii that carbonate sediments or rock may be interfingered with lava flows in the subsurface. This interfingering is the result of the interaction of several geologic processes (e.g., eustatic sea level variation and isostatic crustal adjustment). The thickness of the sedimentary material will, among other factors, depend on the sedimentation rate and the frequency of burial by lava flows.[9] Tunneling or drilling through this relatively soft carbonate (hardness 3) is preferable to a tunnel through basalt (hardness 5.5 to 6). The question thus becomes one of the likelihood of such deposits being encountered at the proposed site. For the mixed discharge, another shaft would be required to handle the combined cold and water effluents. An attractive alternative to the mixed water discharge is to use injection wells. A vertical shaft in porous media obviates the need for large off-shore piping systems and their inherent high costs and risks.

As the technology is site specific, to design a tunnel or drilled hole requires test hole drilling and/or geophysical surveys.

Ideally, a 12-in. test hole would be drilled, logged, and tested by pumping the hole. This hole would provide information on lithologies and the thicknesses of layers as well as the permeability of the rocks.

A second possibility would be to drill a small-diameter hole, similar to a minerological exploration hole, to provide information on lithologies and thickness. Such a hole could not be pump tested because of its small diameter. The slim hole has the advantage of being less expensive ($380,000 to $500,000) than a large-diameter test hole ($780,000).

Information on the structure of an area may also be obtained through geophysical surveys. The geophysical methods include seismic refraction and reflection surveys (commonly called seismic profiles), electrical resistivity soundings, gravity surveys, and magnetic surveys.

The seismic reflection method of geophysical testing would yield the most information. This method uses sound waves reflected from layers of different sonic velocities to determine the material structure. Velocities increase with density, water content, and compaction. The degree of reliability of seismic velocity measurements improves above the ground water table and where the difference in wave propagation velocity between two adjacent materials increases. Seismic reflections are complicated if, as is expected at Keahole Point, there are many cracks and fissures.

A second commonly used geophysical investigative tool is a resistivity survey. The resistance a material has to the passage of an electrical current depends on the chemical composition and degree of saturation of the material. The resistivity method applies an electrical current to the ground through two electrodes. The changes in potential across the known distances between these electrodes are then used to help evaluate material types. Resistivity surveys usually provide the most useful information when they are made in conjunction with a seismic study.

Geophysical methods have the advantages of being nondestructive and relatively fast, and having a low unit cost (~$70,000). However, their precision is usually also low and, hence, the results must be used with care.

An exploratory test hole at Keahole is absolutely necessary before any of the drilling or tunnel boring concepts can be thoroughly evaluated. This test hole should be 9 to 12 in. in diameter and should be sunk at least 3000 ft down.

The test hole would have several purposes. It would

- Determine the precise geology at a selected site
- Determine the porosity and permeability of selected zones
- Test the mixed effluent discharge concept.

Information from this exploration could then be provided to tunneling and drilling contractors for further evaluation of the concepts.

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