R 725

Technical Report

CONCEPTS FOR DRILLING AND EXCAVATING IN AND BELOW THE OCEAN BOTTOM

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CONCEPTS FOR DRILLING AND EXCAVATING IN AND BELOW THE OCEAN BOTTOM

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by

E. J. Beck, T. L. Culbertson, P. J. Daly,
H. A. Gaberson, and A. L. Scott

ABSTRACT

In support of planned development of construction systems for precise excavation and drilling in the deep ocean floor, a study of the potential problems which might be encountered has been made. Two Deep Ocean Technology (DOT) efforts are considered, and two major subsystems are described. The first subsystem is a seafloor excavator which can shape the ocean floor, prepare trenches and drill shallow foundation holes. To avoid the problems of man in undersea environment, this equipment will be unmanned, and remotely controlled by computer and/or numerical techniques. The primary work function will be similar to a conventional milling machine, with similar ability to bore shallow holes. The second subsystem is for penetration of ocean bottom rock with large holes, sealing off the cavity with a prepared steel structure, dewatering, and lateral tunneling at one-atmosphere pressure. Initial penetration will be by equipment similar to large mining or tunneling moles; recent technology in rock disintegration may allow use of a less massive machine with low thrust and torque.

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Buoyancy systems						
Spoil removal						
Remote control of equipment						
Casing methods						
Rock penetration						
Rock fragmentation						
Sealing and dewatering excavations						

CONTENTS

INTRODUCTION

This report presents information on the problems involved in ocean subbottom drilling and excavating. This study is the first step in the development of equipment and techniques for extensive construction site preparation on, in, and beneath the ocean floor. Because so much of the ocean's bottom is at depths where divers cannot function safely and efficiently—if at all—emphasis is on programmed or highly controlled equipment which can function automatically or with a minimum of semiremote supervision from a nearby operator in a one-atmosphere vessel.

While the deep ocean provides a remote, formidable, and hostile environment for doing the simplest of tasks, there are some aspects of this environment which may lead to accomplishing the planned work in a more straightforward fashion than for similar tasks on land. Because the density of seawater is high compared with air, the handling of very large weights by buoyancy techniques is technically feasible at the present time. With increasing depths, the cost of pressure-resistant buoyancy materials increases, and usually their density also increases to achieve the necessary pressure-resistance capability. Thus when suitable materials and control systems are developed, weight handling promises to be simpler and more effective, though more costly in the ocean than on land. Although it might be possible to mechanically subdivide, blow and disperse soil in the earth's atmosphere, the practice would not generally be tolerated in any but the most deserted areas. In the deep ocean, on the other hand, the superiority of seawater in comparison with air for conveying particulate matter as a slurry should provide a unique capability for earthmoving equipment to machine a site to a preplanned contour and eject the resulting slurry into a current or to deposit it some distance from the work site, if the current is inadequate. For many one-time simple assembly tasks, high-pressure seawater will be usable as a hydraulic fluid for locking subassemblies together, etc., if a small receiver is furnished to provide the necessary pressure drop across the working piston.

It is the purpose of this report to define the problems foreseen, assess the state-of-the-art in the relevant equipment technologies, and to define the development work which is believed necessary to accomplish the goals. Where the technology is deficient, explicit statements of the research and development necessary will be found at the end of each section; these are intended as technical work statements for specific efforts, no matter where the research and developmental efforts are conducted.

The research and development is to be conducted on two Navy Deep Ocean Technology (DOT) work units authorized by the Chief of Naval Material (1969) and described as Subprojects WBS 3.1420 of Project 46-36X, which is in turn described in the Technical Development Plan of the same number. The titles of the respective Subprojects are respectively: "Excavators and Dredgers"* and "Drilling and Tunneling."

The first of these subprojects is concerned with shallow excavation and drilling preparatory to making emplacements on or in the soil surface at the bottom of the ocean. Technological development is complicated by the fact that the soil may vary from a gelatinous, almost nonviscous water-filled clay with little shear strength to solid, strong rock.

The second project involves (1) penetrating and shoring against a soil or silt overburden to solid rock; (2) penetrating competent rock with a large diameter hole, probably cylindrical; (3) sealing the opening with a prepared access hatch; and (4) dewatering and excavating large lateral and vertical cavities in a one-atmosphere environment. An alternative and probably more difficult method would be to tunnel from adjacent land and make functional site openings to the sea through the seafloor.

The operational ocean depths considered in this study are all beyond diver depths. It is anticipated that most of the mechanical systems developed will be made essentially depth-independent by having the pressure-sensitive components in pressure equilibrium with the surrounding ocean. For those pressure-sensitive components such as buoyancy pontoons, which must function at full ocean pressure, 6,000 feet is the initial target, with eventual capability to 20,000 feet.

Two major work systems fulfill the aims of the DOT tasks, with several minor systems in support:

1. For the Seafloor Excavator the major piece of equipment foreseen is a mobile chassis, probably with rubber tires for firm bottoms and an interchangeable low-ground-pressure track system for low-shear-strength materials. A track system will be needed for the worst cases and probably will be functional for most bottoms. The unit will receive power through an umbilical, either as electrical power or high-pressure seawater. The vehicle will have a cutter system capable of leveling, trenching, and drilling shallow foundation holes to a prepared plan, under computer and/or numerical control. Several

* In FY 70 designated "Seafloor Excavator."

methods of programming are suggested for investigation. Minor subsystems will consist of specialized work tools which might be adapted and supported by the controlled arm carrying the soil mill and slurry handling system.

2. The final form of the system for large hole boring and lateral tunneling is not so clearly defined at this time. This is because of the need to exploit potentially important developments in new machines that take advantage of new methods for comminution (disintegration) of hard rock. Using present cutter technology, short tool life, high torques, and large thrust would make operation of a large "underwater mole" extremely expensive and difficult, as it would probably have to be frequently brought to the surface for cutter replacement during the boring of an initial large diameter hole. If any of the three alternatives to rolling cutters discussed in the text are used, it may prove practicable to bore the initial hole with systems not using tool bits or cutters, or at least to develop methods which will both extend the life of the bits and reduce the size of the machine, and the torque and thrust on the work face.

Subsystems for this major system will include methods of sealing, dewatering the hole, and tunneling laterally in a one-atmosphere pressure environment beneath the ocean bottom. In the lateral tunneling, novel comminution techniques promise to provide methods which will make otherwise nearly impossible excavation practicable.

POWER TRANSMISSION SYSTEMS

Ideally, machines for construction work on or in the ocean bottom should be operable in the subsurface environment and thus be independent of weather, waves, and large, expensive tenders. The amounts of power required to accomplish the foreseen tasks in a reasonable time are significant and not economically supplied by power from storage batteries. Bottom-sited power sources with the desired capacity are few and, unfortunately, not fully developed. First in desirability would be a small nuclear reactor of the types recently proposed by Gulf General Atomic Inc. (1968) and Atomics International (1968 and 1969). Both the reactor designs and necessary associated technologies appear to be sufficiently advanced to allow further development; however, the design, certification, licensing and testing of useful models for this ocean application are not underway. The Air Force is seriously considering the Atomics International small nuclear plant (SNAP) for independently powering future missile sites. The SNAP reactor has been highly developed for space applications. Its adaptation to ocean use would actually permit simplification of the space and missile application because of the superior cooling and shielding provided by the deep-ocean water (Beck et al, 1964); Braun, 1965; Beck, 1966). Nevertheless, the necessary demonstration, design, and testing will be expensive and require considerable time.

No less expensive to develop than nuclear power sources would be suitable fuel cells. These are also in an advanced state of development for space applications and would be made more efficient by the favorable environment provided by the ocean. However, use of fuel cells instead of a nuclear reactor would introduce an additional logistics problem—the transportation of fuel to the work site. An extensive literature search indicates that costs and time for the necessary development of fuel cells are comparable to those for a small reactor but the resupply problem would make them less attractive in the long run.

A case is made below for use of hydraulic power on the vehicles and in their controls. It should be noted that both the reactor and fuel cell power sources can supply hydraulic power in a simple, closed system and should be considered competitive with surface power systems with some form of power transmission to the bottom.

A primary problem of excavating and drilling on the ocean bottom is that of transferring power from the surface to the subsurface operations if a bottom-sited power source is not used. To determine how this transmission of power could be most effectively accomplished, several power transmission systems were investigated, and efficiencies and size relationships were estimated under pertinent parameters. Electrical, hydraulic, mechanical, and pneumatic systems were studied; each was to deliver 100 hp (equivalent to a power consumption of 74.6 kw) at a depth of 20,000 feet. The conclusions drawn would be similar for the systems at 6,000 feet.

Electrical systems employing (1) three-wire, three-phase alternating current or (2) single-conductor direct current with the ocean used as one side of the line were considered at several voltages.

Hydraulic systems using both petroleum-based hydraulic fluids and filtered seawater as a hydraulic fluid were compared with pneumatic systems. Finally, efficiency of transmission of power from the surface via reciprocating and rotating taut steel cables was analyzed.

The first tentative analysis considers in detail the line losses between the surface and the bottom and the probable reliability of the various systems. Some predictions of the difficulties and effort needed to develop what appear to be the more promising systems are included.

In considering the tentative results of the analysis, it should be kept in mind that the probable method of final power application to working tools at the bottom will be hydraulic, in the interest of reliability. The calculated efficiency of transmission may not reflect the desirability of a system. A seawater hydraulic system pumping filtered water from the surface and using (and discharging) the water at the tool will require no later conversion and would therefore provide what appears to be a very simple and probably highly reliable system. On the other hand, presently available hydraulic motors are not adapted to use of a nonlubricating fluid such as seawater; development necessary to make the system feasible is currently underway (NCEL, 1969). The proposed taut cable systems would require a minimum of development for adapting existing oil well equipment and could develop high pressure in a hydraulic system with any type of fluid.

Comparison of Electrical Systems

The three-phase alternating-current system (Figure 1) and the single-conductor direct-current system (Figure 2) were analyzed using several different wire gages to deliver a terminal voltage of 440 volts and 4,160 volts.

The performance of the three-phase AC system was calculated using the basic equation:

$$P = \sqrt{3}\, E\, I \cos\phi \qquad (1)$$

where P = power (watts)

E = voltage

I = current

ϕ = phase angle

Balanced Y-connected loads were assumed and the slight line capacitance was disregarded. Figure 3 displays the various effects of wire size on a system with a terminal voltage of 440 volts AC. To reach at least 50% efficiency, 00-gage wires must be used. However, as seen in Figure 4, at 4,160 volts number 6 wires will function with over 94% efficiency and number 14 wires will operate with an efficiency of 74%. The three-phase system, although performing with high efficiencies, has to insulate high voltages from a salt water environment. However, this voltage leakage problem is not as severe in the three-phase system as it is in the DC system.

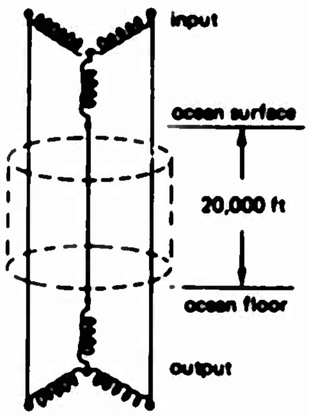

Figure 1. Three-phase AC cable system.

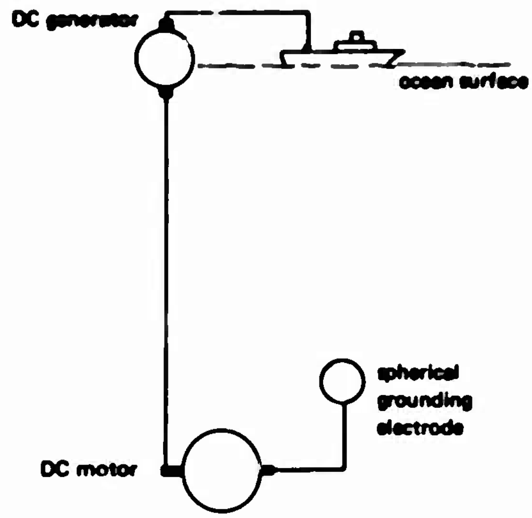

Figure 2. DC deep-ocean cable system.

The greatest inefficiency of the DC system calculated with Joule's equation, $P = EI$, was reflected in the voltage drop across the transmission line. Using the equation (Pender, 1949),

$$R = \frac{P}{4\pi b}\left[\frac{1}{2}\left(1 + \frac{b}{2Z}\right)\right] \qquad (2)$$

where R = interface resistance (Ω)

P = environment resistivity (ft Ω)

b = radius (ft)

Z = depth (ft)

In the case with Z = 20,000 ft

$$\frac{1}{2}\left(1 + \frac{b}{2Z}\right) = \frac{1}{2}$$

thus

$$R = \frac{P}{8\pi b} \qquad (3)$$

Energy losses at spherical grounding electrodes were found to be small and losses through the ocean were considered to be negligible because of the tremendous ocean volume. Results of the DC calculations are presented in

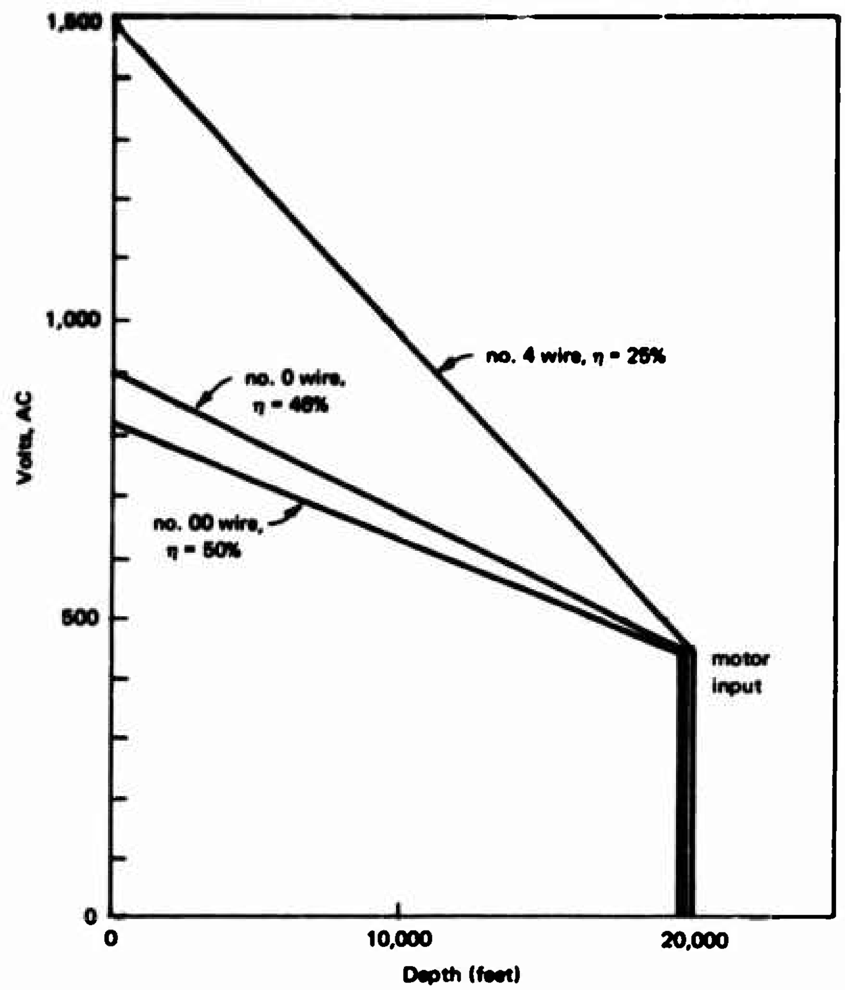

Figure 3. Voltage loss gradient for three AC cable systems.

Figures 5 and 6. The system with terminal voltage of 4,160 volts was more efficient than the system with terminal voltage of 440 volts. A single-line DC system is very compact and efficient but, it has three disadvantages. First, this type of system would be very susceptible to short-circuiting to the ocean environment anywhere along the transmission line and at bottom electrical equipment, because any breakdown in the insulation of the transmission line results in a direct short. With fish biting and abrasion, insulation breakdown could be a major problem. Second, the efficiency of the grounding electrodes would be reduced by electrolytic corrosion. Third, power distribution and conversion at the ocean floor would be difficult since the DC voltage would have to be converted to AC voltage before transformation, or the DC power would have to be converted to hydraulic power.

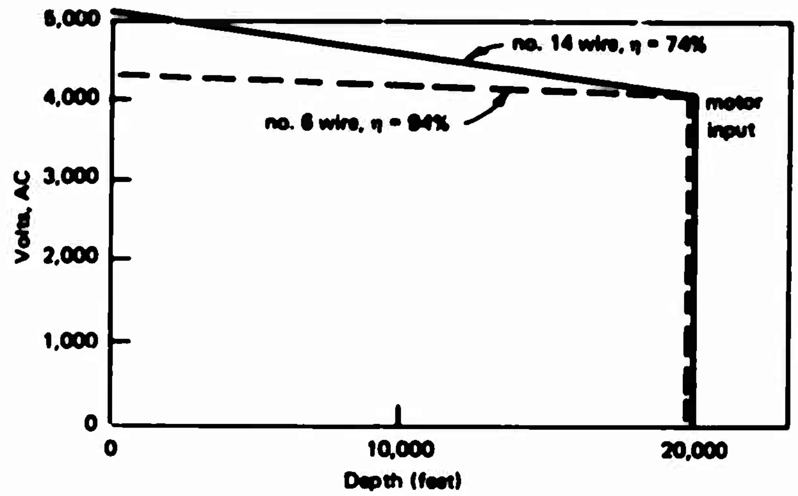

Figure 4. Voltage loss gradient for two AC cable systems.

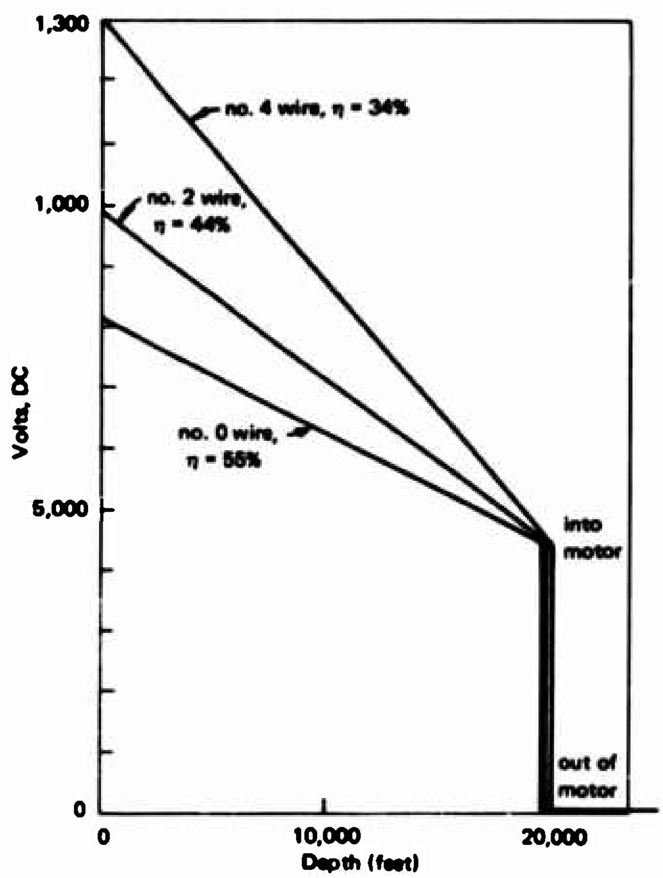

Figure 5. Voltage gradient for three one-wire DC systems.

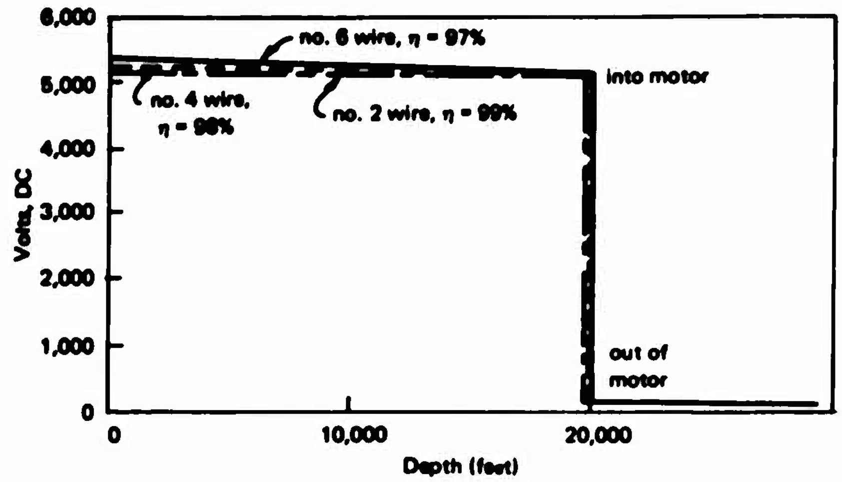

Figure 6. Voltage gradient for three one-wire DC systems.

Comparing the two systems, the AC system seems to be preferable, even though it is less compact and efficient than the DC system. The AC system is less susceptible to shorting since an insulation breakdown in one line results in a no voltage leakage and a breakdown in two separate lines would not be disastrous to the system (Figure 1). Also, as previously stated, the AC system is less susceptible to corrosive deterioration. Finally, induction motors can operate completely submerged while a DC motor requires commutation, necessitating a sealed, oil-filled commutator.

Comparison of Hydraulic Systems

Two working fluids, oil (conforming to MIL-S-5606) and filtered seawater, were considered in the hydraulic calculations. The oil was investigated only in a closed (recirculating) system, while the seawater was considered in both a closed system and in an open system exhausting near the ocean floor.

The performance of the closed oil system (Figure 7) was calculated, using Moody's curves for friction factors (Moody, 1944) and the friction factor equation

$$f = \frac{h_L}{(L/D)\left(\frac{V^2}{2g}\right)} \qquad (4)$$

where f = friction factor

h_L = pressure drop (ft)

L = hose length (ft)

D = hose inside diameter (ft)

V = fluid velocity (ft/sec)

g = gravity (ft/sec)

The results are presented in Figures 8, 9, and 10. The major inefficiency of this system was presumed to arise from friction losses in the line. It should be noted in these figures that a decreased flow rate results in a substantial increase in efficiency, but requires a higher pressure at the motor and therefore a stronger hose. The available commercial hydraulic hose limits application of the oil hydraulic system because when usable efficiencies are reached, the hoses cannot withstand the collapse pressures developed by the density difference between oil and seawater. Hoses of 2-inch inside diameter with a working pressure of 5,000 psi and of 4-1/4-inch inside diameter with a working pressure of 3,000 psi are available but both hoses have a collapse pressure of 400 psi (Knechtel, 1967). Thus, considering only static head pressure, a vertical oil-filled line would collapse at about 9,000 feet below the surface.

The seawater hydraulic concept was investigated as a closed system (Figure 11) and an open system (Figure 12) with flows of 29 gpm, 57 gpm, and 86 gpm, as required for motor pressure drops of 6,000 psi, 3,000 psi, and 2,000 psi respectively in order to obtain the required 100 hp at the ocean floor. For this analysis, the same Moody curves and friction factor equation were used as for the oil system calculations. The results of the seawater hydraulic investigations are presented in Figures 13 through 18. Note should be made that good efficiencies can be obtained by reducing the fluid velocity of the system; however, as seen in the plots of hydraulic gradient, a decrease in the fluid velocity requires an increased system pressure and a stronger hose.

Comparing the three hydraulic systems listed, the open seawater hydraulic system is the most efficient and compact. By using a hose of 2-inch inside diameter with an operating pressure of 5,000 psi (Knechtel, 1967), the filtered seawater open system (57 gpm and 2-inch inside diameter) can be operated with 85% efficiency. The use of seawater also eliminates the hose collapse problem.

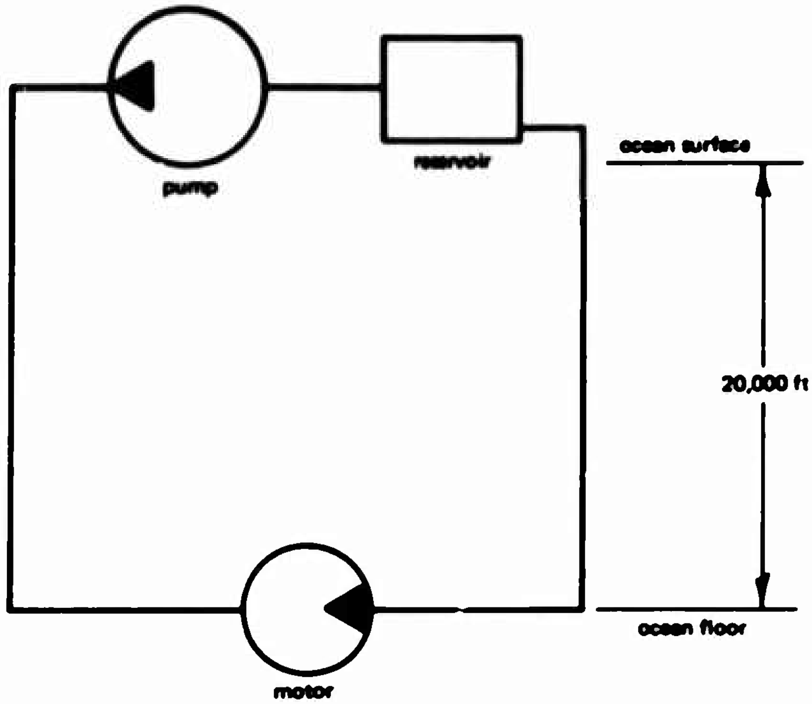

Figure 7. Two-hose closed hydraulic system.

Comparison of Mechanical Systems

Two mechanical approaches to power transmission were considered: (1) the use of a taut cable to transmit linear motion to drive a hydraulic pump on the ocean bottom (Figure 19) and (2) the use of a taut cable to transmit rotary motion to drive a hydraulic pump on the ocean bottom (Figure 20). In both systems, the major and only significant power loss was presumed to be due to skin-friction drag in the water. Either system will require a relatively heavy mass on the bottom. The bottom mass for a reciprocating cable system must exceed the maximum cable tension at the hydraulic pump on the bottom so that the cable can be held taut. The rotating cable must be constantly in tension to avoid coiling.

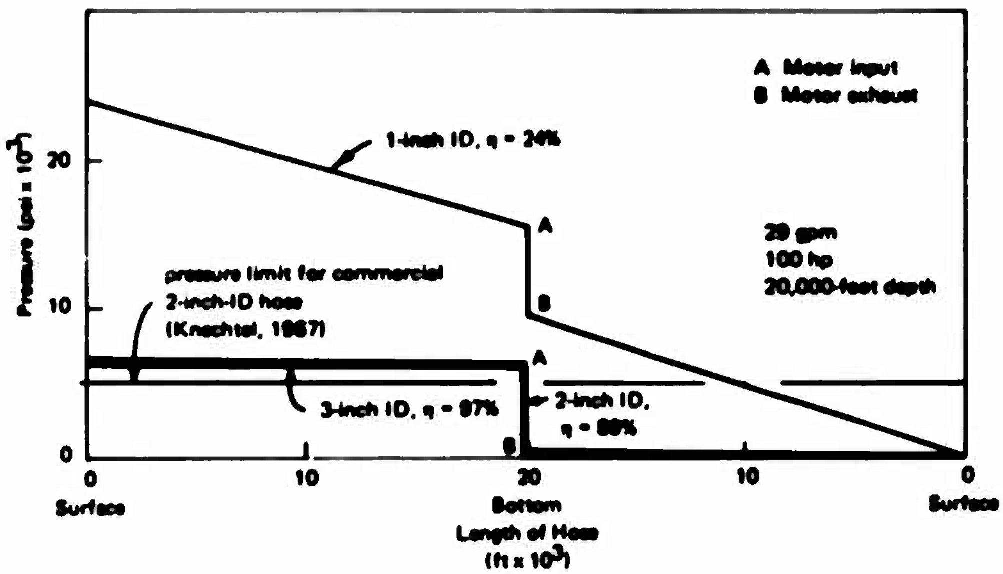

Figure 8. Hydraulic gradient for three two-hose oil systems: 29 gpm.

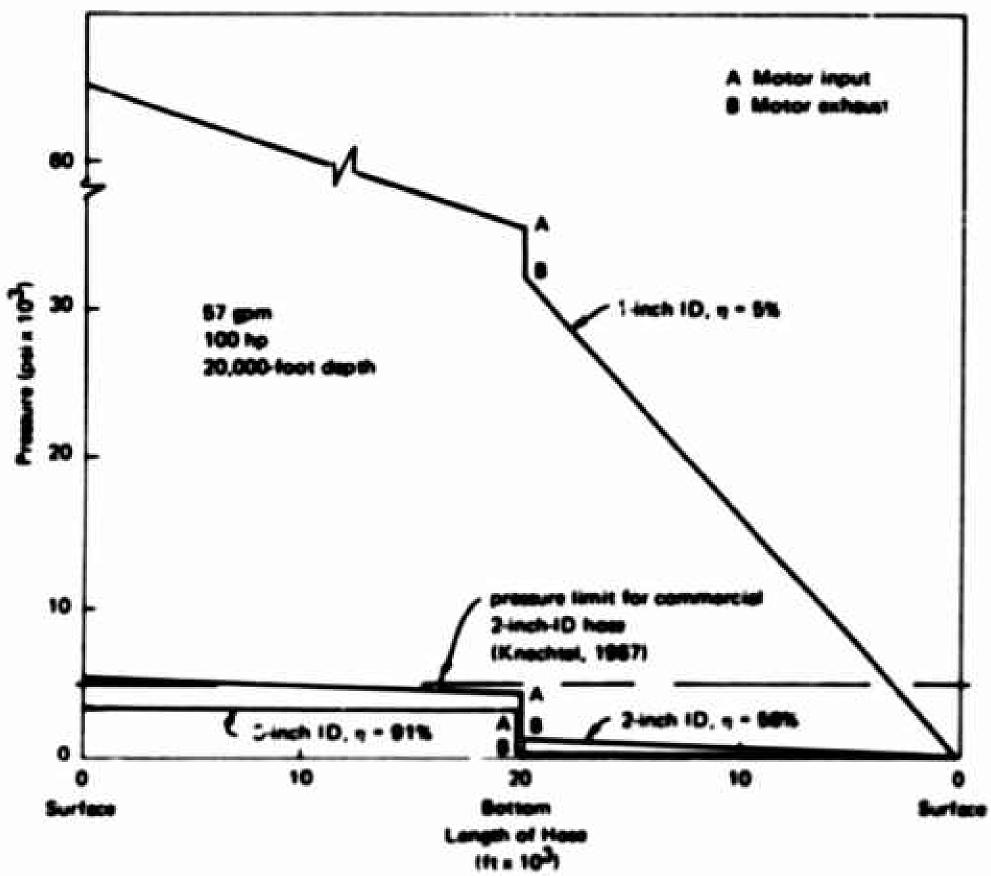

Figure 9. Hydraulic gradient for three two-hose oil systems: 57 gpm.

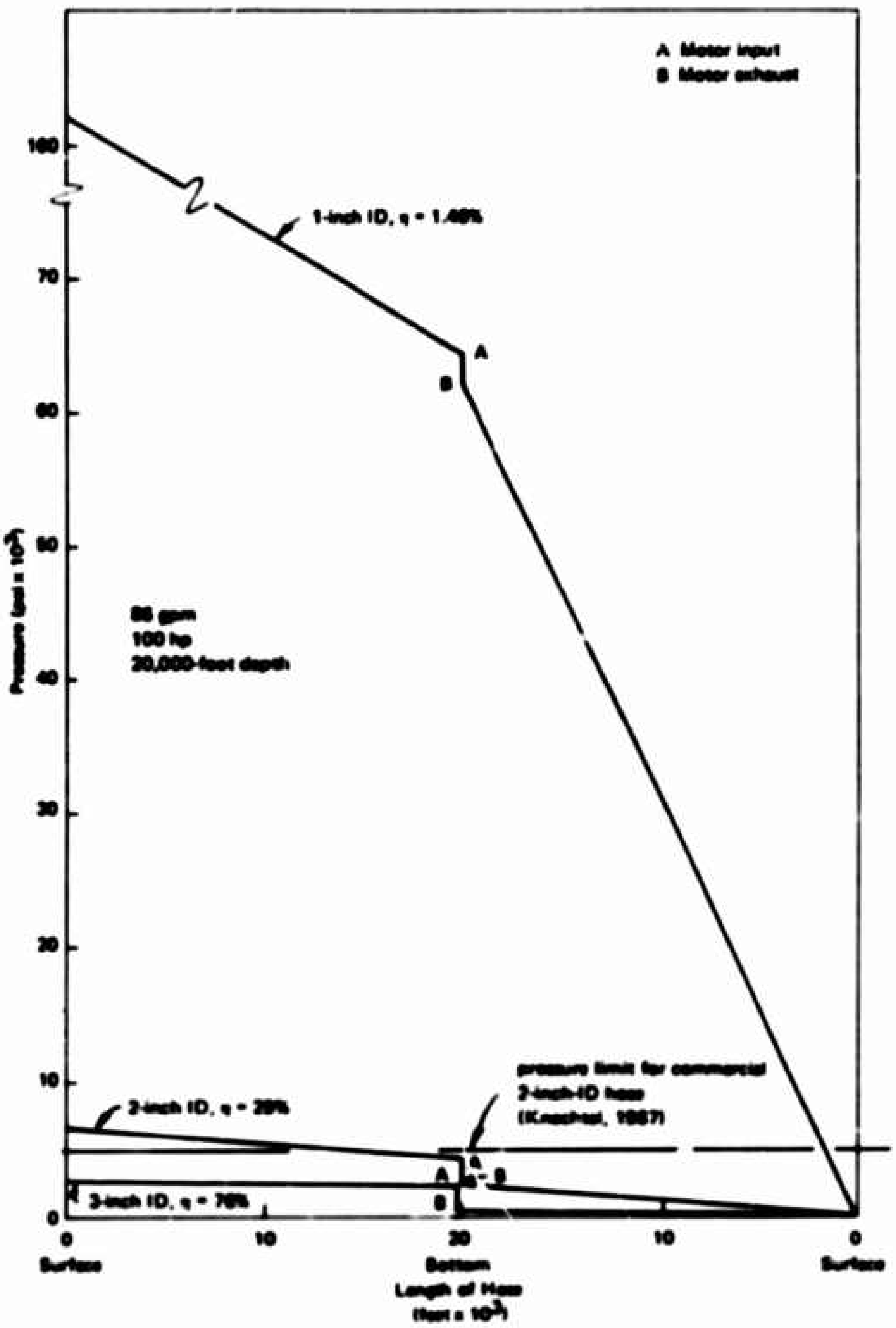

Figure 10. Hydraulic gradient for three two-hose oil systems: 86 gpm.

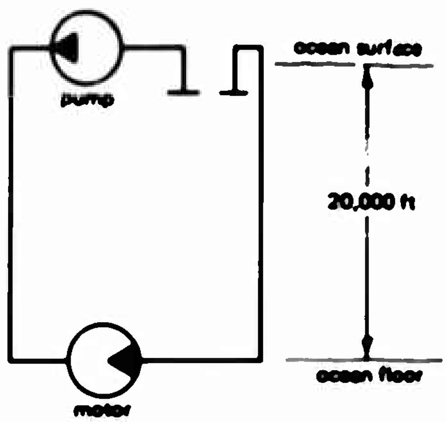

Figure 11. Closed seawater hydraulic system.

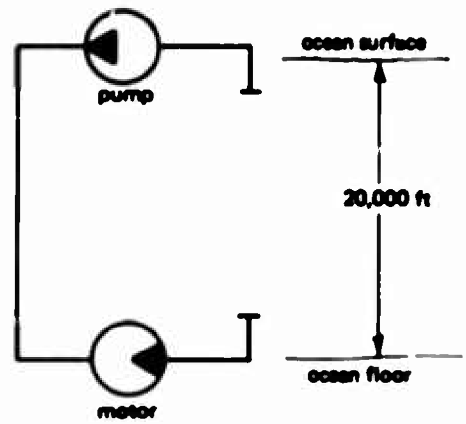

Figure 12. Open seawater hydraulic system.

For the linear-motion cable system, the required input horsepower to develop 100 hp on the ocean floor with cable velocities of 10 ft/sec and 5 ft/sec are given in Table 1. Using 1-inch galvanized bridge rope with a tensile strength of 90,000 pounds, the input horsepower was calculated—presuming that the only resistance forces were skin friction and the retardation imposed by the hydraulic pump, since the cable's weight would be counter-balanced. Applying the equation (Daugherty and Francini, 1965),

$$F = C_f \frac{V^2}{2} B L$$

where F = drag force

C_f = friction-drag coefficient

V = cable velocity

L = length of surface parallel to flow

B = transverse width

the efficiency was found high at either velocity, with the better efficiency at the lower velocity.

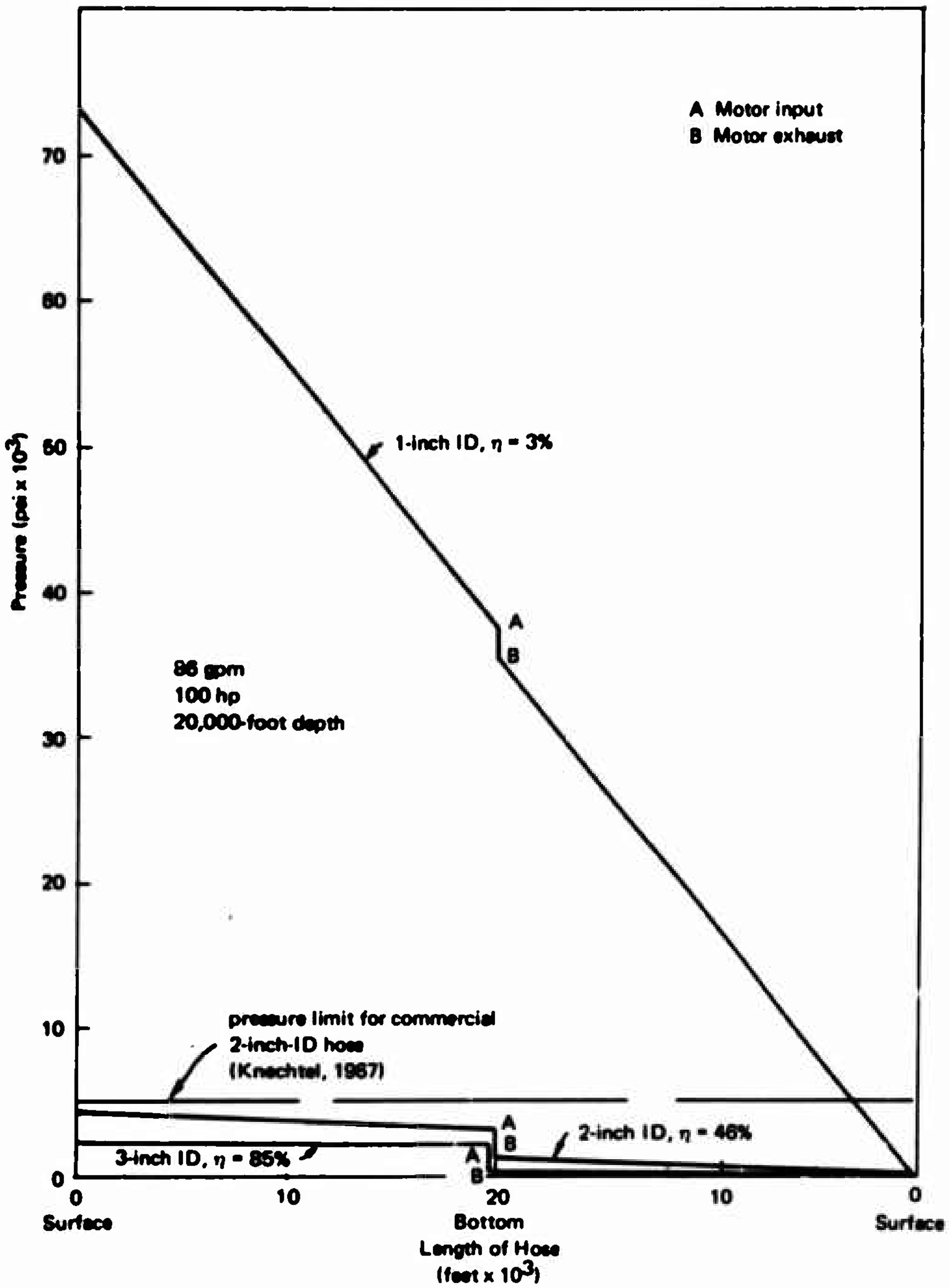

Figure 13. Hydraulic gradient for three two-hose filtered seawater systems: 86 gpm.

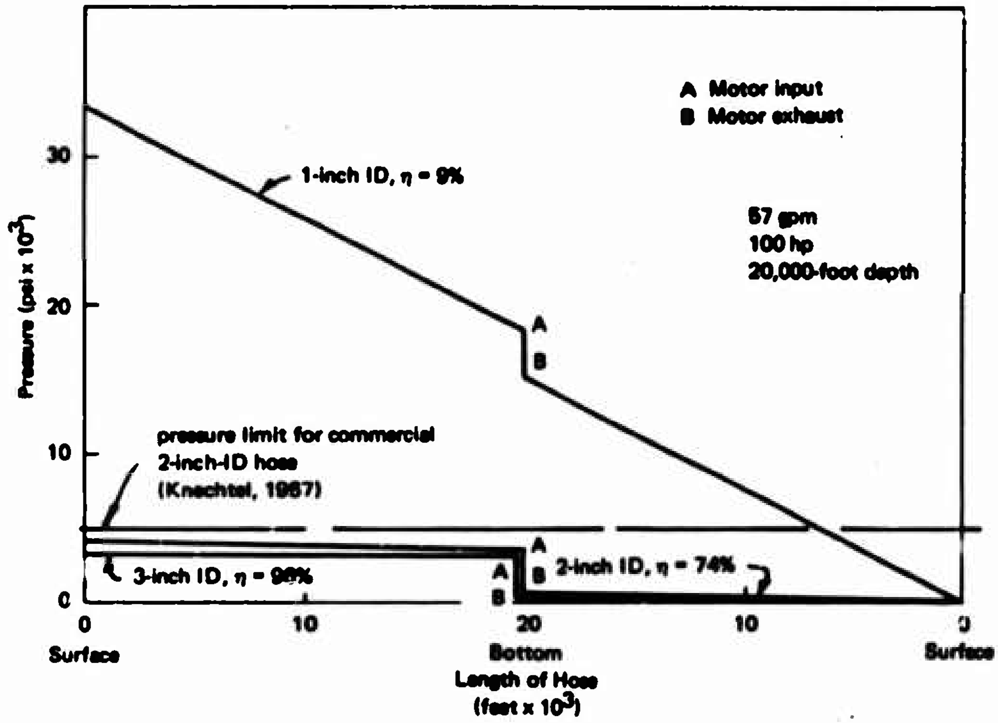

Figure 14. Hydraulic gradient for three two-hose filtered seawater systems: 57 gpm.

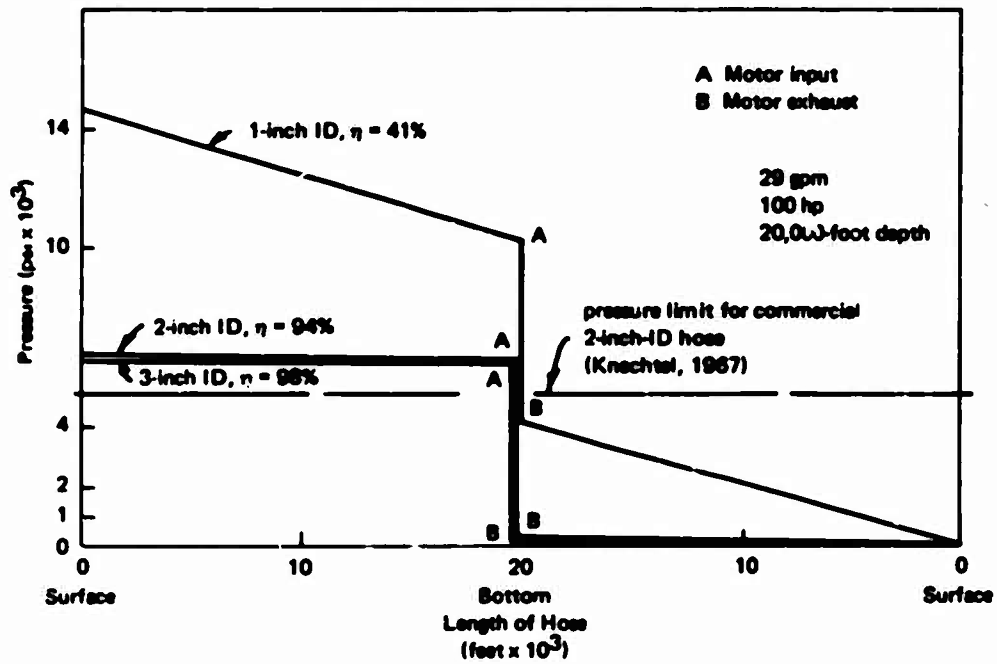

Figure 15. Hydraulic gradient for three two-hose filtered seawater systems: 29 gpm.

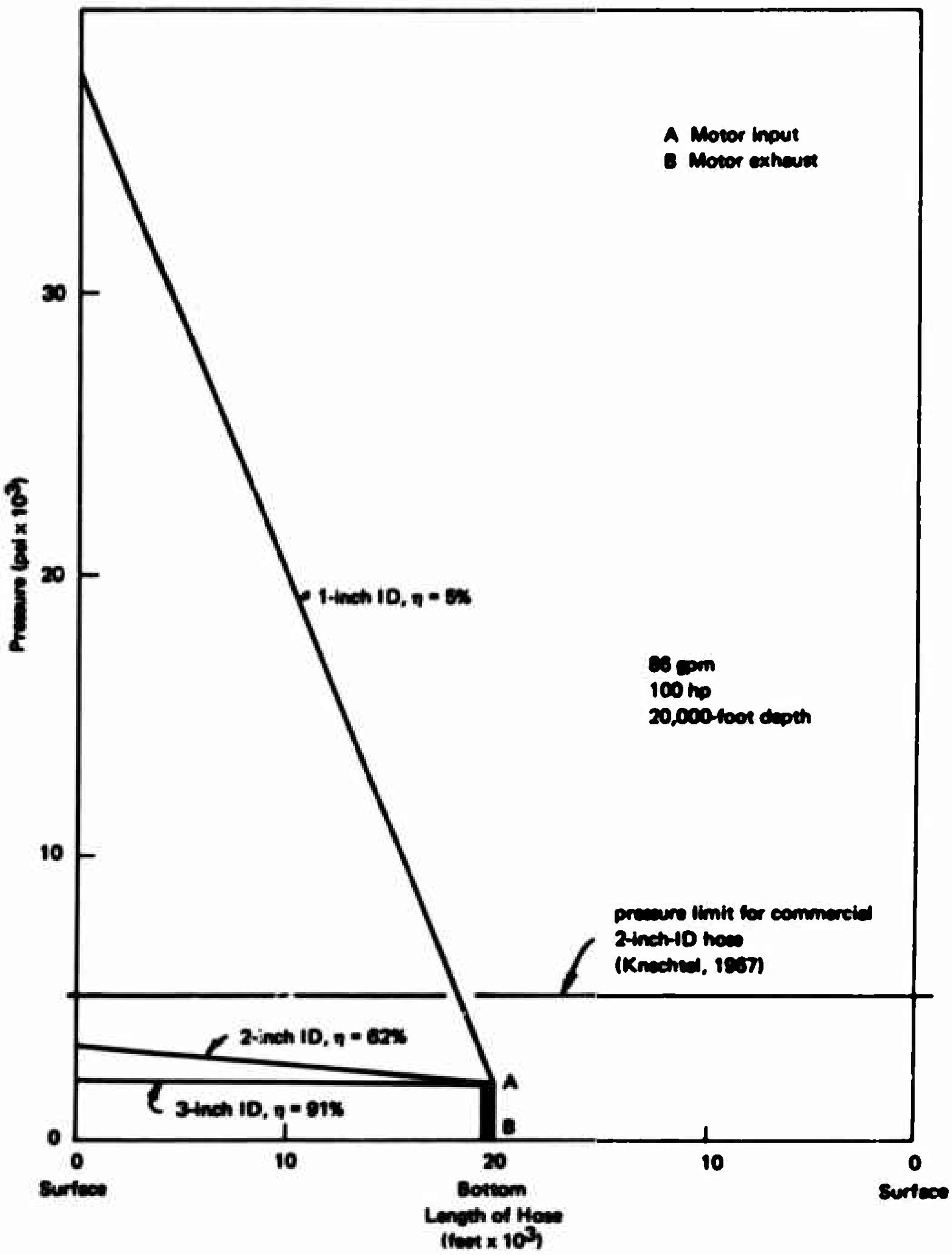

Figure 16. Hydraulic gradient for three one-hose filtered seawater systems: 86 gpm.

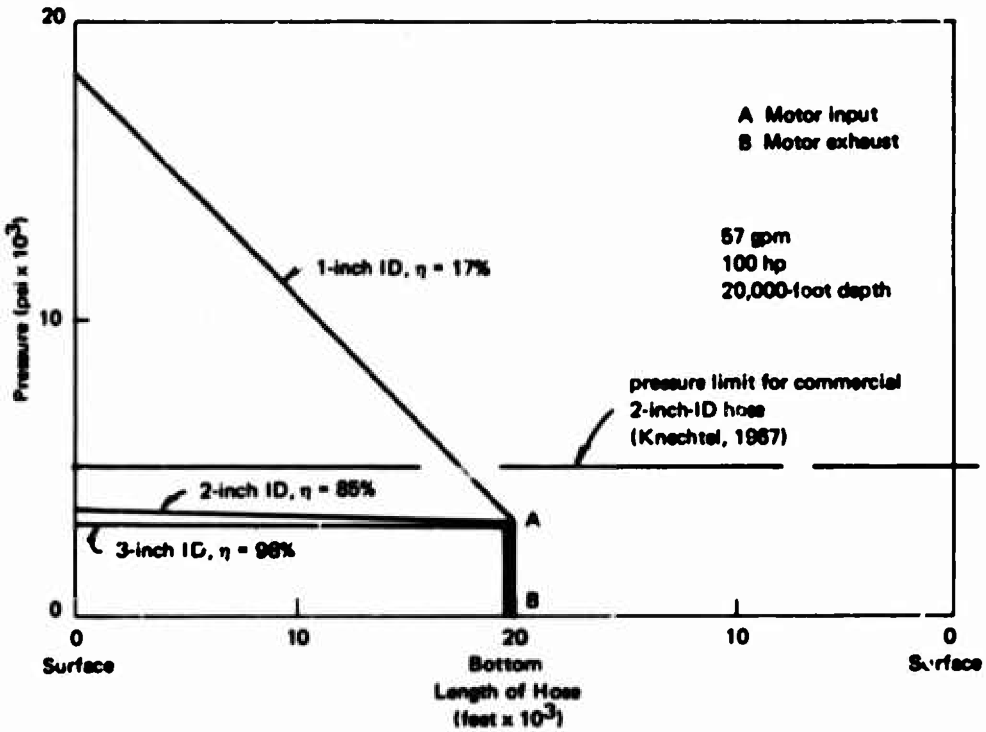

Figure 17. Hydraulic gradient for three one-hose filtered seawater systems: 57 gpm.

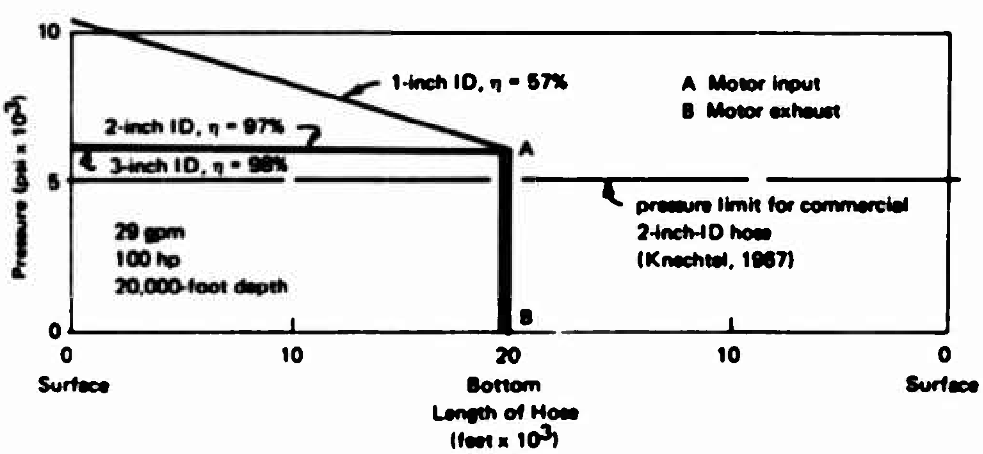

Figure 18. Hydraulic gradient for three one-hose filtered seawater systems: 29 gpm.

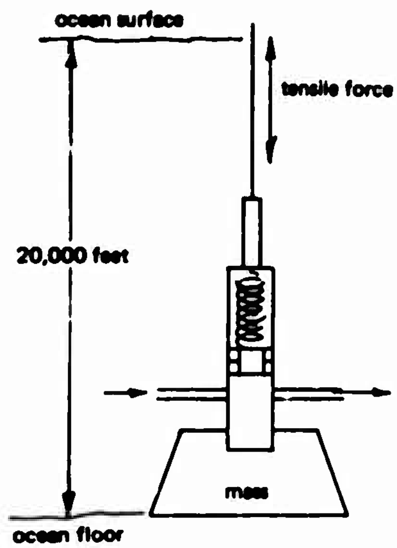

Figure 19. Schematic of linear-motion cable power transmission system.

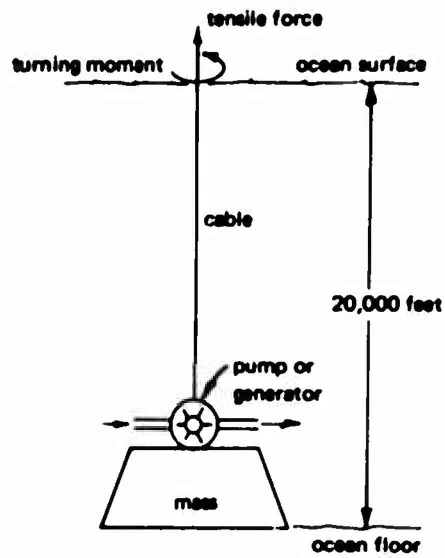

Figure 20. Schematic of rotary-motion cable power transmission system.

The rotating cable system was analyzed by applying Petroff's equation for a journal bearing with no radial load (Shaw and Macks, 1949):

$$F = (2\pi r L)\left(M \frac{2\pi r N}{60c}\right) \qquad (6)$$

where F = friction force (lb)

r = radius (in.)

L = length (in.)

M = viscosity (reyns)

N = rotation speed (rpm)

c = boundary (in.)

The results for rotating a galvanized bridge rope at three different angular velocities are presented in Table 2. It should be noted that with low angular velocities, the skin friction and input horsepower are low. However, to transfer power equal to that of a higher angular velocity, a low angular velocity requires a large power torque necessitating a larger and heavier cable.

Table 1. Efficiency of Linear Motion Power Transmission System Using Taut Cable (See Figure 21)

Cable Diameter (in.)	V (ft/sec)	Power Force (lb)	Skin Friction (lb)	Horsepower	Efficiency, η (%)
1	10	5,500	612	111	90
1	5	11,000	166	101.5	98.5

Table 2 Efficiency of Rotary Motion Power Transmission System Using Taut Cable (See Figure 22)

Cable Diameter (in.)	Turning Speed (rpm)	Power Torque (ft-lb)	Skin Friction Torque (ft-lb)	Input Horsepower	Efficiency, η (%)
2	1,000	525	61	112	89
1	10,000	52.5	76.4	243	41
3	50	10,500	1.03	≈100	99.9

Although using the ocean wave motion to drive the linear motion system is conceivable, this source of energy was eliminated from consideration because of its inconsistent occurrence and magnitude.

Since any severe vertical motion could damage or incapacitate either cable system, some method of support must be used to block out the wave motion, such as mounting either mechanical system in a tall vertical cylinder spar. This spar would be less susceptible to vertical ocean motions than a simple hull.

Pneumatic System

The pneumatic power transmission system was investigated as a closed circuit (Figure 21) and an open circuit (Figure 22), with line pressure loss as the major source of inefficiency.

The analysis was made by considering three layers of slight temperature change as isothermal layers and then applying in each layer the equation (Marks, 1958):

$$P_1 = P_2^2 + \frac{2w^2 R T_Z}{gA}\left(1n\,\frac{v_2}{v_1} + \frac{2f'L}{D}\right) \qquad (7)$$

where P = pressure at indicated point (psi)

w = weight fluid flowing (lb/sec)

R = perfect gas constant

T = temperature (^oR)

g = acceleration of gravity (ft/sec^2)

A = area of section (ft^2)

v = volume per unit weight (ft^3/lb)

f' = friction factor, f/4

L = length of hose (ft)

D = inside diameter of hose (ft)

Simple heat-transfer calculations proved the assumption of isothermal flow in these layers to be valid since the air flows were low enough that complete heat transfer was accomplished.

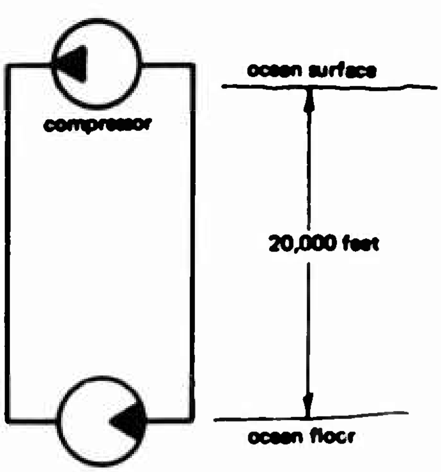

Figure 21. Schematic of closed-circuit pneumatic system for power transmission.

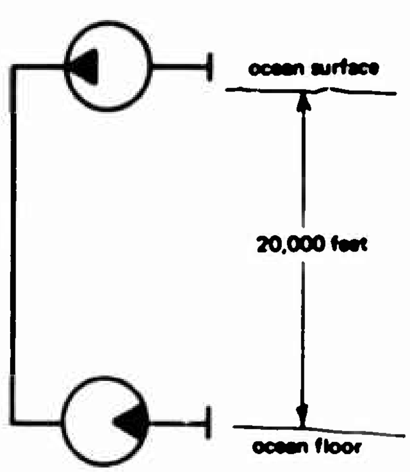

Figure 22. Schematic of open-circuit pneumatic system for power transmission.

Figures 23 and 24 display the results of varying the air flow in 1-inch-ID piping. Although low efficiencies were the result of using 1-inch-ID piping, the small diameter must be used because larger pipes are subject to crushing at low pressures. The problem of crushing arises because air has a much lower density than the seawater and thus develops only a slight static head. To prevent collapse, the system air pressure would have to be raised. This would result in (1) lower efficiencies if this excess pressure was throttled to the atmosphere or (2) a more complicated system if the circuit was completely closed and thus maintaining an initial pressure head. Also, large pipes have relatively low bursting strength, and thus thick-walled pipe would be required near the surface, where there is very little external pressure on the piping.

The closed-circuit pneumatic power transmission system was found to be more efficient than the open circuit, since the energy lost by line flow was less than the energy lost be exhausting into a pressure of 9,000 psi. However, both systems would have to be operated with rigid pipes because of the high pressure and both systems require large input horsepowers because of their low efficiencies. The reason for the low efficiencies can be seen in a pressure volume diagram (Figure 25). When the system has a high exhaust pressure, very little of the work expended in compressing the air is used to drive the pneumatic motor. However, with a low exhaust pressure as in shallow depths, most of the energy input for compression is used to drive the pneumatic motor.

Conclusions

Of the four basic power transmission systems investigated, only one, the pneumatic system, does not warrant further study. It would require excessive line pressure and rigid pipes and would have low efficiency.

The open-circuit seawater hydraulic system and the three-phase AC system were comparable in efficiency. While both schemes have high efficiencies, they require high potentials near the surface, 4,330 volts AC for the electrical system and 6,160 psi for the hydraulic system. Operating at 57 gpm through a 2-inch-ID hose, the open-circuit seawater system has an efficiency of 85%. The available 2-inch-ID hose has a 4.75-inch outside diameter and a weight of 17.5 pounds per foot. This weight would have to be supported by a tension cable or a series of buoys. The three-phase electrical system with three number 6 wires in a 1.97-inch diameter cable has an efficiency of 95%. This electrical system is not as bulky and heavy as the hydraulic systems and thus is more applicable to greater depths.

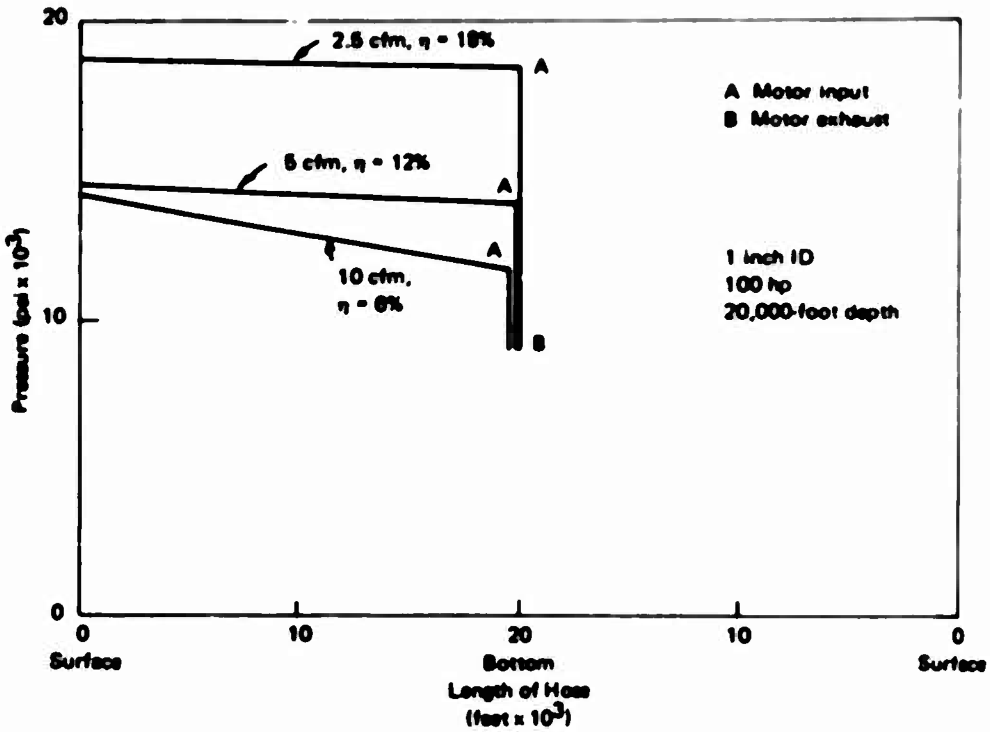

Figure 23. Pressure gradient for three one-pipe pneumatic systems.

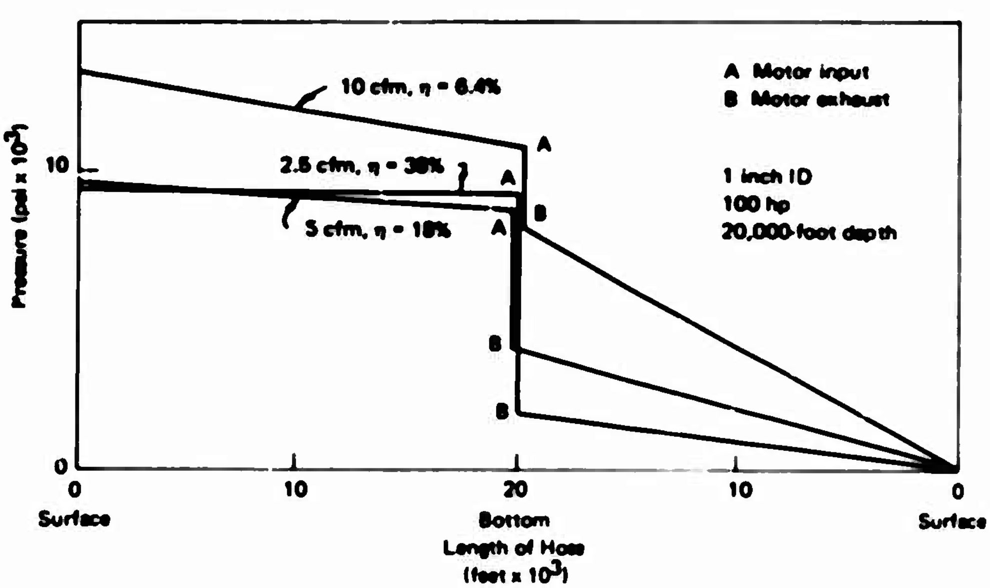

Figure 24. Pressure gradient for three two-pipe pneumatic systems.

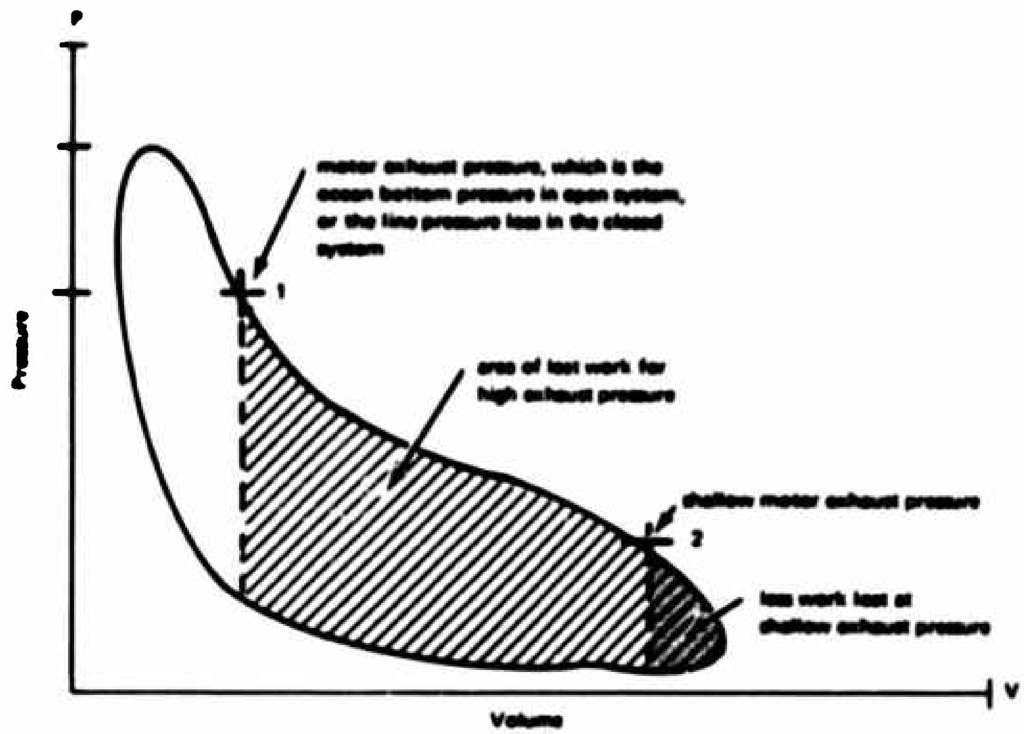

Figure 25. Pressure-volume diagram for pneumatic systems.

Only one of the mechanical transmission systems, the linear-motion system, was found to be compact and efficient. This cable system required a 1-inch-diameter galvanized bridge rope and produced efficiencies as high as 98%. This system is extremely simple and is free from some sources of failure that affect electrical and hydraulic systems—shorting or leaking along the transmission line.

Either the three-phase AC system or the linear-motion cable system can be developed with commercially available materials. However, the mechanical scheme is the more reliable and simpler of the two.

Summary

In shallow areas to about 2,500 feet, the one- and two-hose filtered seawater systems can operate at good efficiencies with the hose unsupported. At greater depths, the one-hose system is more efficient than the two-hose system, but the hose will have to be supported by a tension cable or a series of buoys.

The mechanical and electrical system can be used at all depths with high efficiency, but it is desirable for each system to convert its power to hydraulic power at the ocean floor site for reasons presented in the next section. The linear-motion cable system appears relatively simple, inexpensive, and rugged; it will require a minimum of development. It produces the desirable hydraulic power directly.

Future Plans

Depending upon the state-of-the-art in electrical power cables at the time that decisions must be made on selecting a power transmission system, some effort may be needed to develop an alternate system. No immediate effort is planned, except in the development of seawater hydraulic motors which could utilize a high-pressure hose for power transmission in an open seawater system (NCEL, 1969). There is some possibility of a simple experiment with reciprocating and rotating cable power transmission systems (Figure 26) as part of SEACON experiments in early 1971.

POWER TRANSFER AND CONVERSION SYSTEMS

Power Transfer

In the absence of fully developed self-contained generating systems capable of operating on the ocean bottom, it will be necessary to conduct bottom operations with power supplied from the surface or on a bottom-laid conductor from the shore. The three known potential systems of possible merit transmit energy as electricity, hydraulic pressure, and as a force in a rigid system, as discussed in detail in the previous section. The means of conducting power in the three cases are insulated electrical cables, hydraulic hoses, and reciprocating or rotating steel wire cables, respectively. Because the optimum system (best from a cost-effectiveness standpoint) for transmission may not be the best for supplying power to a specific piece of equipment, an additional trade-off study is needed to establish the best combination and the most effective method for converting from one form of power to another at the bottom. An additional complicating factor may arise if it proves necessary or desirable to transmit power from the surface to a stationary unit and then locally through distribution channels. The distribution lines or hoses necessary to supply power to a mobile or semi-mobile platform (Figure 27) could easily become fouled by crawler tracks or moving machine parts. Therefore, the connecting system would undoubtedly require buoying to keep it off the ocean bottom—a simple solution because of the high density of seawater.

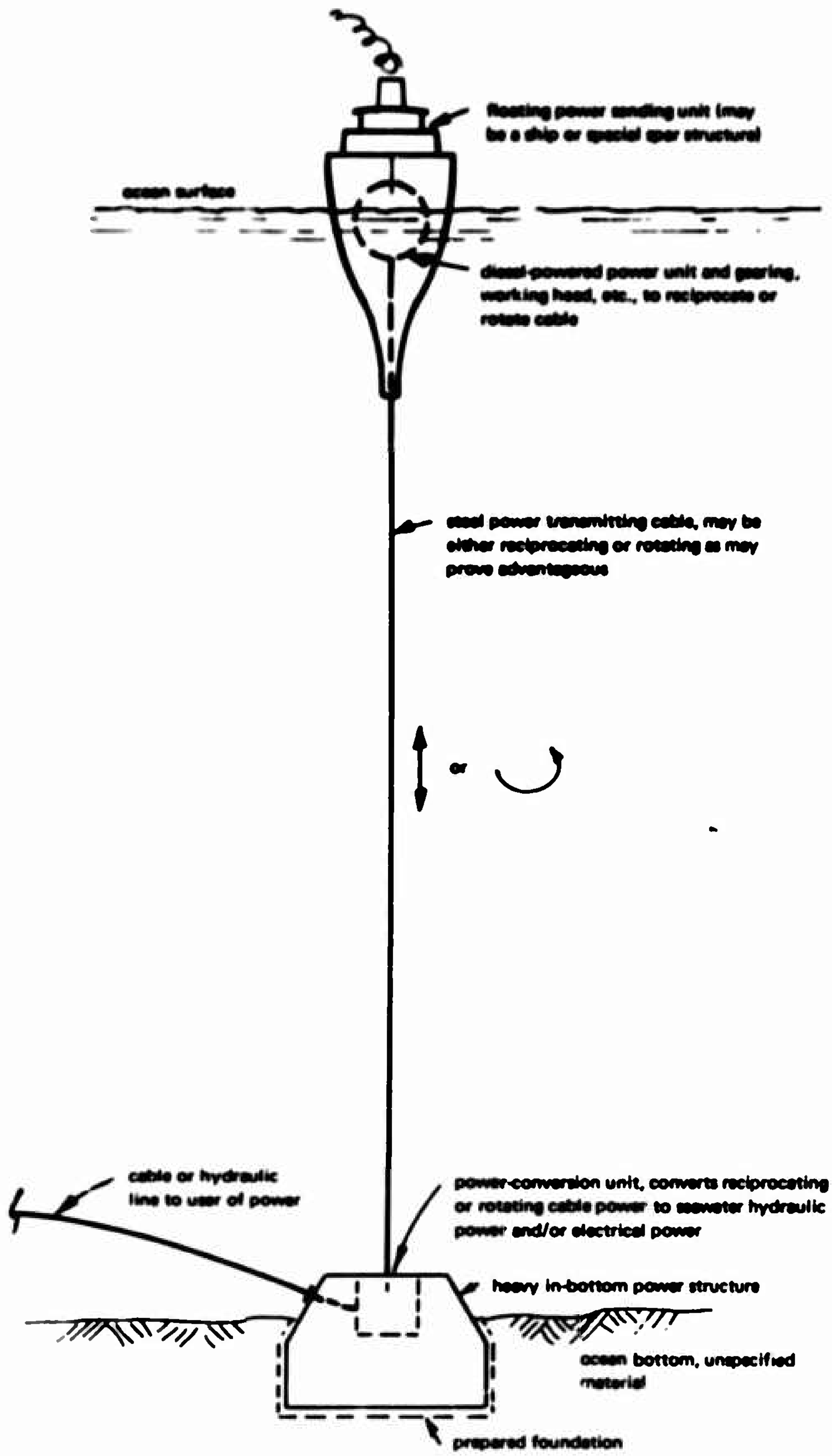

Figure 26. Proposed reciprocating or rotating cable power transmission systems.

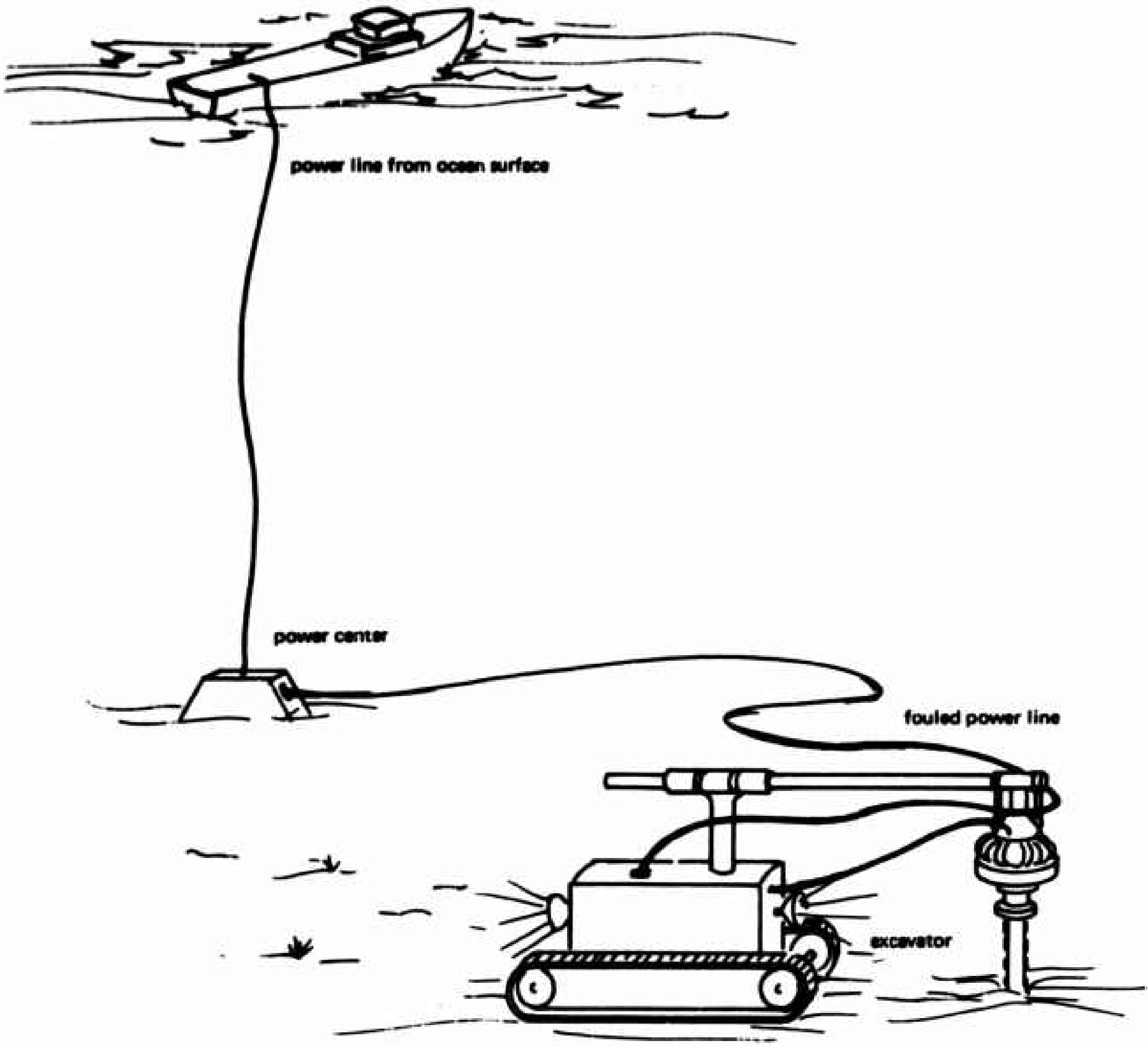

Figure 27. Potential problem in working a tethered seafloor machine.

To insure development of the most reliable total system possible, it is planned to use power in the minimum number of forms practicable. Because of the torque-limiting characteristics of hydraulic motors, actuators, and controls, it appears that a maximum use of hydraulic components will be advisable. If power is supplied to the work site and to the working platform through an electrical cable, a central hydraulic pump driven by a totally sealed electric motor will be needed. Whether the hydraulic system will be filled with a petroleum base hydraulic fluid or uses filtered seawater is probably of small consequence, except that precaution must be taken with the oil-filled system to assure that leakage will be from, not into, the system. The seawater system, when developed, will be simpler in that only one line will be needed, and the discharged water may be used in jet pumps at the work point. What appears to be the simplest system might be one in which filtered seawater is pumped under pressure from the power source on the ocean surface to the bottom and then is used in a simple open circuit and discharged at the work point. This approach appears particularly desirable for moderate depths; collapse of the hose would pose no threat, as discussed in the previous section. Suitable hoses are available (Knechtel, 1967); these are sometimes referred to as flexible pipes and are quite rigid and strong in tension. The system needs only the satisfactory development of high-pressure pumps and motors capable of working on filtered seawater, a development well underway and with a high probability of early success.

Power Conversion

Hydraulic systems have seen increasingly wider applications in mobile equipment for the operation of auxiliary equipment, due to their flexibility and compactness (Bowers, 1967). In the ocean, the advantages of hydraulic systems become more pronounced due to their freedom from the hazard of electrical shock and from the unwanted effects of buoyancy and compressibility. However, the problem of contamination due to leakage does exist. The contamination may involve the typical working fluid, hydraulic oil, by seawater and result in rusting of metal parts (Evans, 1964) and degradation of the performance of the hydraulic oil (Anderson and Brown, 1965); or it may involve the atmosphere of saturated diving chambers if the hydrocarbons contained in hydraulic oil are volatilized when hydraulic tools are brought into the chambers for maintenance or storage (SEALAB III Atmospheric Contamination Bill, 1967).

One promising solution to this problem is the use of seawater as a hydraulic fluid. In addition to eliminating the contamination problem, several other benefits would accrue. Principal among these would be the use of the ocean as a reservoir allowing the use of an open-cycle hydraulic circuit. The open-cycle circuit eliminates the need of a reservoir other than the ocean for fluid storage and cooling. Also eliminated is the return hose, thereby cutting piping friction losses approximately in half. This is especially advantageous if a long hose is used as is the case when power is to be transmitted from a pump on the surface. Schematics of a closed-cycle seawater hydraulic circuit and an open-cycle hydraulic circuit are shown in Figures 11 and 12.

A complete hydraulic circuit requires a high-pressure pump, a motor, filters, connecting hoses, and valves for control. Although present filters, connecting hoses, and valves should prove adequate if made of corrosion-resistant materials, investigations at NCEL (Daly, 1969) and NSRDC (Robbins, Schneider, and Mehnert, 1968) have indicated that typical commercial hydraulic pumps and motors will not perform satisfactorily when using seawater as a hydraulic fluid. The early and drastic failures of these commercial units (Daly, 1969) indicate that pumps and motors using seawater as a hydraulic fluid must be carefully designed to compensate for the low viscosity, poor lubricating properties, and corrosive nature of seawater. Proposed uses for this system, such as supplying power to protable diver's tools, also require that the motor design be compact and lightweight and the system pressure be high enough to eliminate large flow requirements. The seawater can be filtered to remove organic materials and sand. However, other treatments such as the addition of lubricants, corrosion inhibitors, or viscosity increasing agents should be avoided because the motor would be used in an open-cycle circuit where the additives would contaminate and be lost in the ocean. Since currently successful lubricating additives have to be present in percentages in excess of 5%, the cost of using these additives would be excessive (Anonymous, 1967a). In addition, the use of additives would introduce the complication of a mechanism for the measuring and mixing of the additive and the logistics problem of keeping supplies of the additives available at the work site, which might be deep in the ocean.

The ratio of the absolute viscosity of seawater (approximately 1 centipoise) to the viscosity of typical hydraulic oils varies from 0.05 to 0.01 depending on temperature (Marks, 1958). The low viscosity of seawater directly affects the performance of pumps and motors by allowing an increase in internal leakages thereby reducing volumetric efficiency. The various high-pressure pump and motor designs are not affected by this low viscosity to the same degree. Units with rotating gears or sliding vanes are relatively simple and compact, but subject to leakage past the gears or rotors. Since the internal leakage is approximately inversely proportional to the viscosity of the working fluid (Hadekel, 1951), the use of seawater as a working fluid will cause a large increase in internal leakage. To counteract this effect, the internal clearances of seawater pumps and motors will have to be reduced, perhaps to as little as 0.0001 inch per inch. These small clearances will impose more stringent requirements on the selection of materials as regards thermal expansion and rates of wear. Sliding vane units also have inherent friction at the point of contact between the vanes and supporting slots and are generally limited to applications with moderate operating pressures. Current commercial models of piston-type pumps are particularly useful because they can work at very high pressures. They are attractive for seawater applications, because leakage can be minimized through use of a long piston and piston grooves (based on the well-known labyrinth sealing principle) to produce a high pressure drop with limited leakage. An experimental high-pressure seawater pump (Figure 28) based on an axial piston design and using ceramic components has been developed by the Naval Ship Research and Development Center (Robbins, Schneider, and Mehnert, 1968). This pump may provide a basis for designing a suitable motor and pump for a seawater hydraulic system, although a more compact design for the motor would be desirable.

The poor lubricating properties a orrosive nature of seawater limit the materials which are suitable for use in the construction of these pumps and motors to those which exhibit low friction, low wear, and low corrosion when wetted by seawater. One very promising material is the 99.5% pure alumina (Al_2O_3) ceramic used in the development of the NSRDC seawater pump. This very hard material (resists 2,100 kg per mm^2) exhibits good mechanical properties, low friction, and low wear when lubricated by seawater (Robbins, Schneider, and Mehnert, 1968).

Although lubricated sliding systems are generally composed of a hard and a soft surface, these systems fail when adequate lubrication is not present. For unlubricated surfaces, two hard surfaces perform better than a hard and and a soft surface. Nonmetals, such as alumina, are better than metals because they do not spot weld and shear (Bowden and Tabor, 1950). Another approach is the use of self-lubricating materials. These materials may consist of a matrix for mechanical strength and a polymeric material for lubrication. One such material is the wood, lignum vitae (Lagally, 1967). Other possibilities include glass-filled Teflon sliding on stainless steel, Teflon fiber fabric and plastic alloys. However, self-lubricating plastics rubbing on hard surfaces usually show high rates of wear which may not be acceptable in critical clearance applications unless there is a compensating mechanism. Another plastic exhibiting low friction in water is "Delrin," a polytetrafluoroethylene (PTFE) filled acetal resin (Anonymous, 1967b). This material has been used in the construction of small high-speed gears lubricated only by seawater (Glasgow and Bartilson, 1968).

One of the more common materials used in the construction of small hydraulic pumps and motors is aluminum. However, aluminum has been found to be unacceptable for use in a seawater hydraulic system (Anonymous, 1967a, and Daly, 1969), at least as used to date.

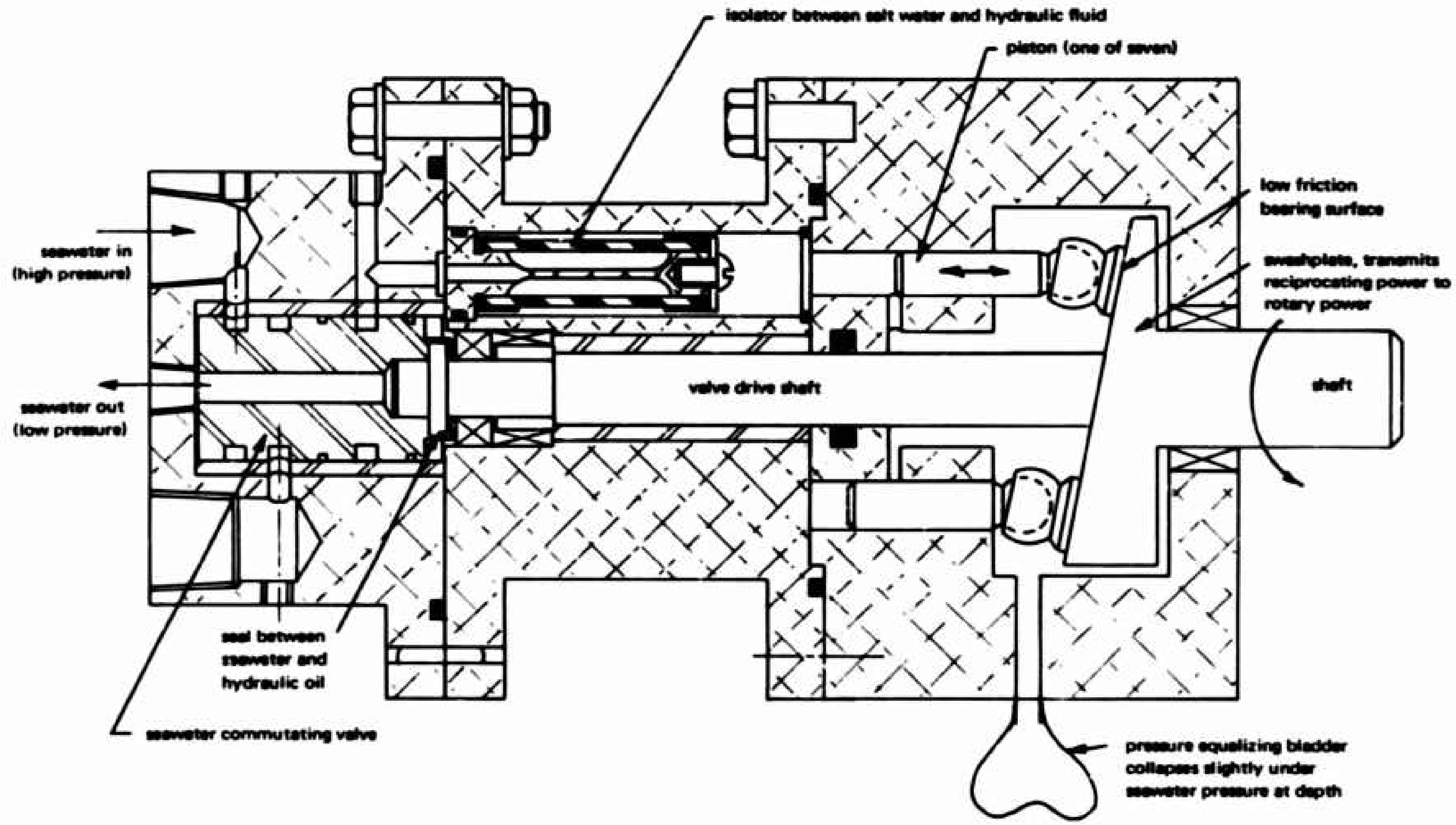

Figure 28. Preliminary design of proposed seawater hydraulic motor.

Although lubrication of the parts of the motor in contact with the seawater hydraulic fluid may not be acceptable, lubrication of the power transmission (that is, swashplates, connecting rod, timing gears, etc.) should prove acceptable if required. Since these units are planned for use in the ocean environment at depths to 20,000 feet (9,000 psi), any lubrication system would have to be designed to prevent seawater contamination of the lubricant at these pressures. It may be possible to prevent contamination by applying a small over-pressure to the lubricant from a spring-pressurized reservoir. This reservoir can probably be quite small for portable tools with short periods of use and submersion. For larger machines, the limitations on size and volume will be less, and the reservoir can probably be accommodated if the concept proves feasible.

The pressures involved at depths up to 20,000 feet create severe sealing problems or require pressure compensation, not only for seawater hydraulic pumps and motors, but for all mechanisms having spaces from which seawater must be excluded. This underscores the desirability of designing a seawater pump or motor to require only seawater as a lubricant.

Another potential problem at ocean depths could be the change of material characteristics with pressure. Possible effects would be change of hardness in elastomers or change of friction characteristics in plastics in a manner analogous to the increase in coefficient of friction or graphite surfaces in a vacuum (Bowden and Tabor, 1950).

Conclusions

The development of a seawater hydraulic pump or motor requires a material compatible for use with seawater. Alumina ceramic is one material having demonstrated a potential for this application. In addition, a trade-off study is required of the simplicity and compactness of the vane- and gear-type units versus the higher volumetric efficiencies but more complex mechanisms of piston-type units. The specific application would also affect this trade-off, since volumetric efficiency is of more concern in pumps, while overall mechanical efficiency, compactness, and light weight are of more concern in the development of a motor unit (Henke, 1965).

Summary

A systems analysis and preliminary design of a Seafloor Excavator have been completed. (See Northrop, 1970, and discussion under "Shallow Drilling and Excavating.") As part of that study and preliminary design, a reliability, weight, and cost comparison was made between an all-electric and an electro-hydraulic system for internal power distribution and control within the recommended mobile concept. While the study showed a marked advantage in reliability and cost, and only a slight disadvantage in weight in the electro-hydraulic over the all-electric system, Northrop's recommendation was still for the electric system. The relative merits of these and other combinations need further intensive study before final judgment can be made.

A considerable body of experience and test data on various components is being accumulated by the Navy Laboratories, and it will become increasingly desirable that this be collated and inspected as each piece of equipment goes into the final design stage. It is proposed that collation of information and the intensive and realistic assessments of the type done by Northrop (1970) be the major effort for the near future.

This preliminary examination of the problem indicates that conversion of power transmitted electrically, mechanically, or pneumatically from the surface to hydraulic power will be the preferred and most reliable approach. When practicable, all components of the Seafloor Excavator and Large Hole Drilling System will be operated through hydraulic power and controls. To avoid sealing problems, the preferred hydraulic fluid would be filtered seawater, but for the near future small-scale subsystem experiments will be conducted with two-hose closed hydraulic systems, pending development of suitable seawater motors.

Future Plans

The objectives of the current development effort are high-pressure pumps and motors with the same advantage as those using conventional hydraulic fluids, but capable of using pressurized seawater as the working fluid. The initial developmental effort of small, compact units suitable for use in conjunction with divers hand-held tools is in progress under a development work unit funded at NCEL by the Supervisor of Salvage, U. S. Navy. Further development will be carried on after FY 70 in the Navy's Deep Ocean Technology Program, especially in the development of drilling and excavating machines usable on the deep ocean bottom. The pertinent DOT work units are: Rotary Cutter and Hydraulic Earth Moving Equipment (Work Unit No. 64-016) and Basic Chassis for Bottom Systems Support of Drilling Equipment (Work Unit No. 64-017).

CHASSIS FOR SUPPORT AND MOBILITY OF EQUIPMENT

There are three basic technical problems in developing a useful underwater construction chassis. First, large equipment weights must be supported at the soil—water interface. Because many bottom materials are semisolids, the ground bearing capacity will be low. Second, while only sufficient traction is needed to allow slow but positive movement, with low-shear-strength soils even this may be difficult to develop. Third, current concepts call for working from an oriented, fixed platform which would be periodically moved--thus the need for traction. Once positioned, the platform must remain stationary during the work period. Low-shear-strength, saturated soils are essentially plastic and appear to have low viscosity under sustained loading. Even small reaction forces from the work tools may be expected to cause some movement of the platform.

Trafficability of the Ocean Floor

In order to support a load and develop traction on the ocean floor, it is necessary to determine the physical characteristics and eventually the load-supporting ability of the materials that make up the ocean bottom. These parameters must then be related to the characteristics of the specific load-carrying devices intended for use.

As the earthmoving or construction equipment must be able to work anywhere on the ocean bottom, it must be designed for operation on soil with the lowest bearing and shear strength known to exist. Because there will be no problem on rock or hard-packed sand and gravel bottoms, only the softer sediments need be considered here.

There are six principal types of sediments found on the ocean bottoms of the world (Keller, 1968). They are: (1) fluvial-marine (sand-silt) representing the coarser fraction (larger than 0.016 mm); (2) fluvial-marine (silt-clay) the finer fraction (smaller than 0.016 mm) of material derived from terrestrial drainage; (3) red clay, a term applied to inorganic pelagic clays which vary considerably in color but are usually chocolate brown; (4) calcareous ooze, used here to identify sediment composed of at least 30% calcium carbonate in the form of skeletal material from various planktonic animals and plants. Globigerina oozes are included in this sediment type; (5) calcareous sand and silt consisting of shell fragments and coralline debris of sand and silt-size particles; (6) siliceous oozes, deposits containing 30% or more of siliceous skeletal material derived from either diatoms or radiolarians.

These sediments cover approximately 75% of the ocean bottom. Calcareous oozes cover 67% in the Atlantic, 36% in the Pacific, and 54% in the Indian Oceans; siliceous oozes cover 7% in the Atlantic, 15% in the Pacific and 20% in the Indian Oceans; and red clay covers 25% in the Atlantic, 49% in the Pacific and 25% in the Indian Oceans (Sverdrup, Johnson and Fleming, 1942).

Generally speaking, the red clays are found at depths greater than 18,000 feet and the oozes between 6,000 and 18,000 feet, according to Marmer (1930).

The load that can be supported by a foundation or a machine depends primarily on the resistance of the soil to shearing deformation. This shear resistance can be measured by various apparatus; the most common method is by compression tests in which an axial load is applied to the specimen and increased until failure occurs. Failure takes place by shear on one or more inclined planes, and it is possible to compute the normal pressure and the shearing stress on such a plane at the instant of failure (Bishop and Henkel, 1957).

A series of shear tests on identical samples of soil, each subjected to a different normal pressure, can be plotted in a diagram showing the normal stress, p, as a function of the shearing stress, s, at the instant of failure. The results for most soils approach a straight line as shown in Figure 29. The equation of the line shown in Figure 29 is:

$$s = c + p \tan\phi \qquad (8)$$

The value c, called the cohesion, is equal to the shearing resistance on the failure plane where the normal pressure on that plane is zero. The angle ϕ is known as the angle of internal friction.

Experience has shown that natural masses of soft clay, if loaded during testing so rapidly that little drainage can occur, usually behave as if $\phi = 0$, in which case the above equation becomes

$$s = c \qquad (9)$$

Under such conditions, shear strength is a function of the cohesion only. Soft clays on the ocean bottom would behave in this manner (Peck, Hanson, and Thornburn, 1953).

Stresses acting within a submerged mass of soil that are transmitted from grain to grain of the solid constituents are called intergranular pressures. Those that act within the water that fills the voids in the soil are called pore-water pressures. Only the intergranular pressures can produce frictional resistance in the soil. It can be shown that the intergranular pressure, $\bar{p}$, on any horizontal plane in the submerged soil mass is equal to the depth, z, of the plane below the soil surface multiplied by the difference in unit weight of the saturated soil, V_{sat}, and the unit weight of water, V_w (Peck, Hanson, and Thornburn, 1953).

$$\bar{p} = z\,(V_{sat} - V_w) \qquad (10)$$

V_{sat} for some red clays has been found to be approximately 89 pounds per cubic foot.

$$\bar{p} = z(89 - 64) = 25z \text{ lb per ft}^2 \qquad (11)$$

Extensive experiments have indicated that the cohesion, c, in soft submerged clay may be as low as 0.25 $\bar{p}$. This gives us a means of determining the shear strength, or cohesion, of this soil at any depth below the soil surface.

$$c = 0.25\bar{p}$$

Therefore, $c = s = 6.25z$

The following table shows the shear strength (or cohesion) for a specimen of red clay from the surface of the ocean bottom to a depth of 10 feet below the soil–water interface. Strengths are shown in both pounds per square foot and pounds per square inch for ease of comparison with other data.

Depth, z	Shear Strength, s	
(feet)	(psf)	(psi)
0	0	0
1	6.25	0.043
2	12.5	0.086
3	18.75	0.129
4	25.0	0.172
5	31.25	0.217
6	37.5	0.260
7	43.75	0.304
8	50.0	0.347
9	56.25	0.39
10	62.5	0.435

The shear strengths shown in this table are small but probably represent the worst case. Other ocean-bottom soils display shear strengths ranging upward from these figures to as much as 25 times greater.

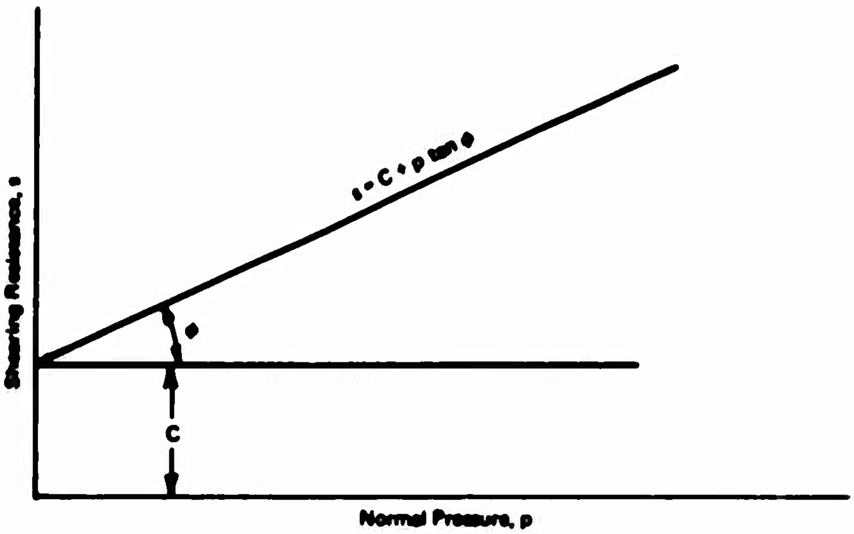

Figure 29. Relation between normal pressure and shearing resistance.

A comparison of the data obtained by the Naval Oceanographic Office (Keller, 1968), shows that sediments in the North Atlantic possess relatively higher shear strengths than do those of the North Pacific. Large areas in the northern portion of the North Pacific consist of sediments possessing shear strengths ranging from 0.25 to 0.5 psi for the upper few feet of sediment. In the lower latitudes of the North Pacific, values of 1.0 to 1.5 psi predominate, and in a few small areas values range as high as 1.5 to 2.5 psi. In the North Atlantic, sediments with a shear strength of 0.5 to 1.0 appear to predominate. The highest values observed in the North Atlantic are associated with calcareous deposits and vary from 1.0 to 1.5 psi, but there is one rather large area of red clay east of Greenland which displays strengths of less than 0.5 psi. For comparative purposes, a piece of modeling clay into which a person can push his thumb easily has a shear strength of approximately 2 to 3 psi.

As shear strength is easily measured, it is used as a means of classifying soils, but when a load such as a platform or a vehicle track is applied, the load-bearing capacity is a more useful index of the soil strength. Figure 30 illustrates the relationship between shear strength and ground load-bearing capacity. As the load sinks into the soil, it pushes a cone of soil ahead of it which displaced the underlying soil to the sides. As the surrounding soil offers resistance to this movement, the displaced soil is forced upward. Shear takes place along the upwardly curving surface, which is much larger than the contact area between the load and the soil. It can be shown that the ultimate bearing capacity of the soil, U, is a function of the cohesion, the length and breadth of the load contact area and the depth to which the load sinks below the soil surface (Peck, Hanson, and Thornburn, 1953). For example, for a track whose length-to-width ratio is 5, in soft clay where $s = c$, and at a depth of 1 foot below the soil surface,

$$U = 5.7c$$

For ocean-bottom red clay at a depth of 1 foot below the soil surface where the shear strength is 0.043 psi, the ultimate bearing capacity for that track would be

$$U = 5.7 \times 0.043 = 0.25 \text{ psi}$$

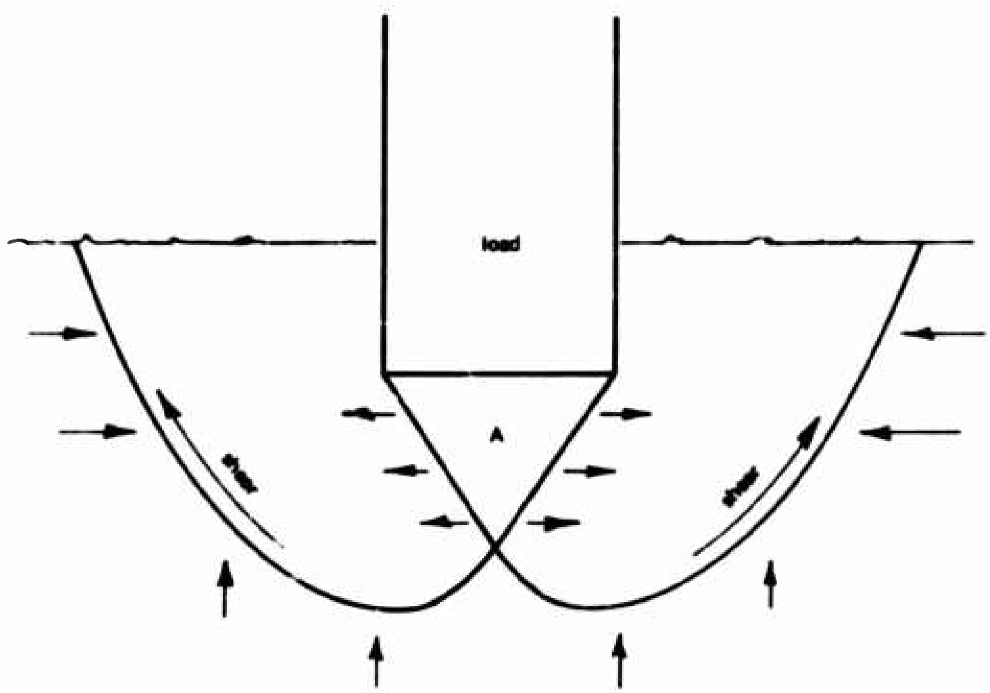

Figure 30. Soil shear path resulting from unconfined compression.

Terrestrial Trafficability Schemes

Although the density of snow at 6 to 18 pounds per cubic foot is considerably less than that of the red clays at approximately 89 pounds per cubic foot, their consistency and shear strengths are quite similar. Consequently, it is felt that the experience gained in testing and operating vehicles in soft wet snow can be of assistance in determining the best type of wheel or track for use on the ocean bottom (Bekker, 1956, p. 160).

Extensive experimentation with both tracked and wheeled vehicles has revealed that for a vehicle to be successful on soft snow, it must have a low, evenly distributed ground pressure, a long narrow bearing area, and small relative sinkage (Mellor, 1963).

The average ground pressure of a vehicle is the vehicle weight divided by the total ground bearing area, and is often quoted as an index of the vehicle's potential for oversnow travel. Since penetration into the soft surface corresponds more closely to the peak stress than to the average ground pressure, the latter can be a misleading index. The distribution of pressures beneath many types of tracks is far from uniform; therefore, they usually sink deeper than might be expected on the basis of a calculated uniform pressure.

The weight of most tracked vehicles is carried on their running wheels, or bogies, which themselves bear on the section of track laid on the ground or snow. With the vehicle stationary, its flexible track is deflected sinusoidally, depression being deepest beneath wheels. The track arches up in the spaces between wheels. When the vehicle moves, the peak stresses pass over all the snow in the path. As a result, sinkage is increased and with a slack track, the wheels are always running uphill on a sinusoidally distorted track. A tight track tends to decrease the uphill angle. Figure 31 (Mellor, 1963) shows schematically the stress distributions beneath four common track types.

When a track or wheel sinks a major fraction of its vertical dimension, it will push, or bulldoze, snow ahead of it, shearing the snow horizontally. This consumes energy that could otherwise be used for tractive effort. Because bulldozing resistance is proportional to track width, a narrow track is desirable to minimize this loss. As a large bearing area is also necessary to provide low ground pressure as discussed above, a long narrow track is indicated. There is a limit, however, on the length of track that can be used on a vehicle with one pair of tracks. The moment of turning resistance is directly proportional to track length, vehicle weight, lateral friction, and load distribution. It has been found that if the ratio of length to gage (width between track centerlines) is greater than 1.7 to 1.9, the vehicle will not turn (Bekker, 1956, p. 76). To eliminate this restriction, some vehicles employ two or more pairs of tracks in an articulated configuration. The length-to-gage ratio of some of these units is between 3 and 4. Examples of this type of vehicle are tabulated in Table 3.

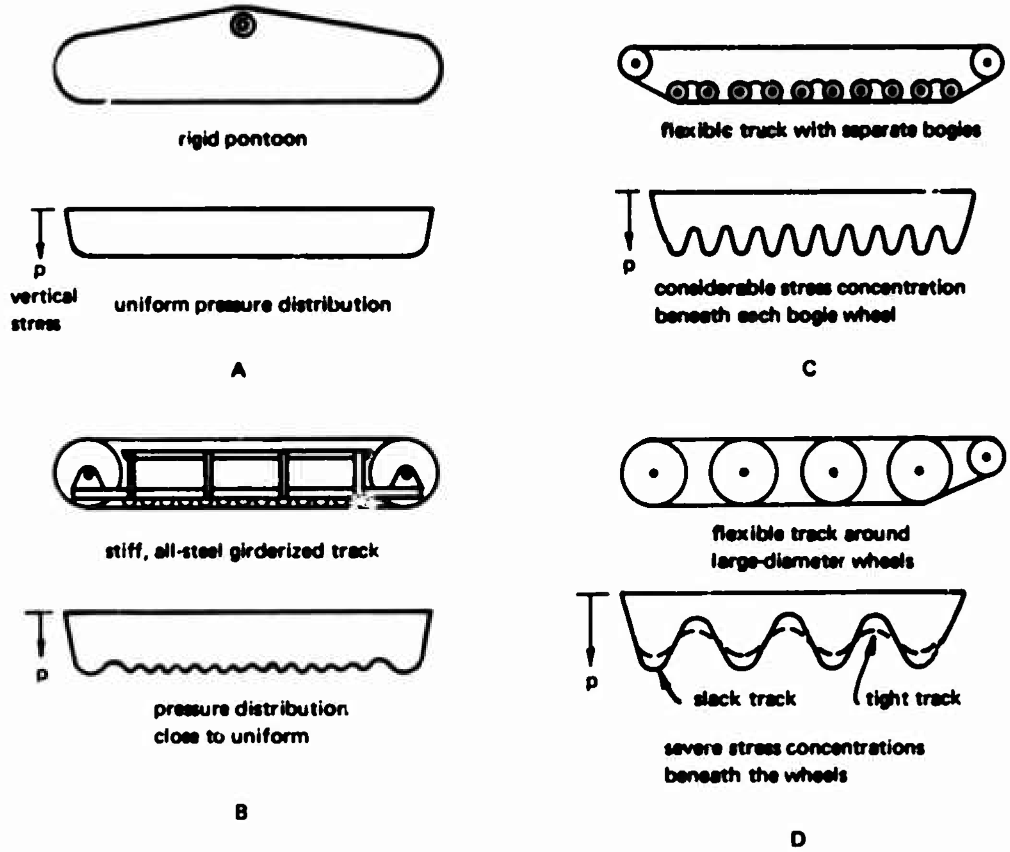

Figure 31. Stress distributions of three track systems.

Most of the heavy prime movers and large overland vehicles used in the Antarctic and other cold areas have one pair of tracks. The Low Ground Pressure Caterpillar Tractors, Models D-8, D-6, and D-4, manufactured by the Caterpillar Company, Peoria, Illinois, and the Russian Kharkovchanka, manufactured by the Kharkova Tractor Works, U.S.S.R., are examples of these units. Although they are called oversnow vehicles, they all have a ground bearing pressure of about 4 psi and must operate on hard surfaces or where there is a shallow, hard subsurface.

Besides the tracked vehicles, there are many other concepts for providing support and traction on soft surfaces that have been tried with various degrees of success. Some of them are discussed below.

Endless Belt. The endless belt is similar to a segmented track but has a rubber belt instead of the linked track. The belt supports the vehicle weight on bogie wheels, but in order to minimize heavy stress concentrations at their points of contact with the soft flexible belt, the bogie wheels are usually more numerous and smaller than bogie wheels on the more rigid segmented tracks.

Table 3. Articulated or Tandem-Tracked Snow Vehicles

Name	Manufacturer	Illustration Reference	Length (ft)	Weight (lb)	Average Ground Pressure (psi)	Performance in Snow
Polecat 1	Wilson, Nuttall & Raimond, Inc., Chestertown, Md.	Figure 32	24	10,000	2.1	satisfactory
Polecat 2		Figure 32	40	24,000	2.6	satisfactory
Musk-Ox		Figure 33	49	50,000	3	satisfactory
Nodwell	Robin, Nodwell Mfg. Co., Ltd., Calgary, Alberta, Canada	Figure 34	39	47,500	2	satisfactory
Tucker Sno-Cat (several models)	Tucker Corporation, Medford, Oregon	Figure 35	16 to 25	2,500 to 21,000	0.91 to 2.1	outstanding, even in deep, soft snow

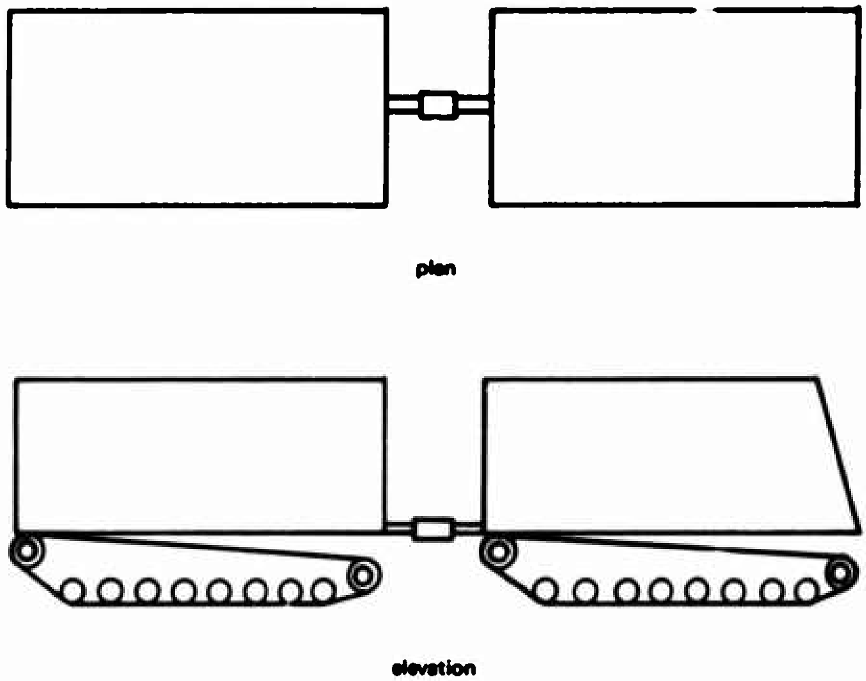

Figure 32. Polecat articulated personnel carrier.

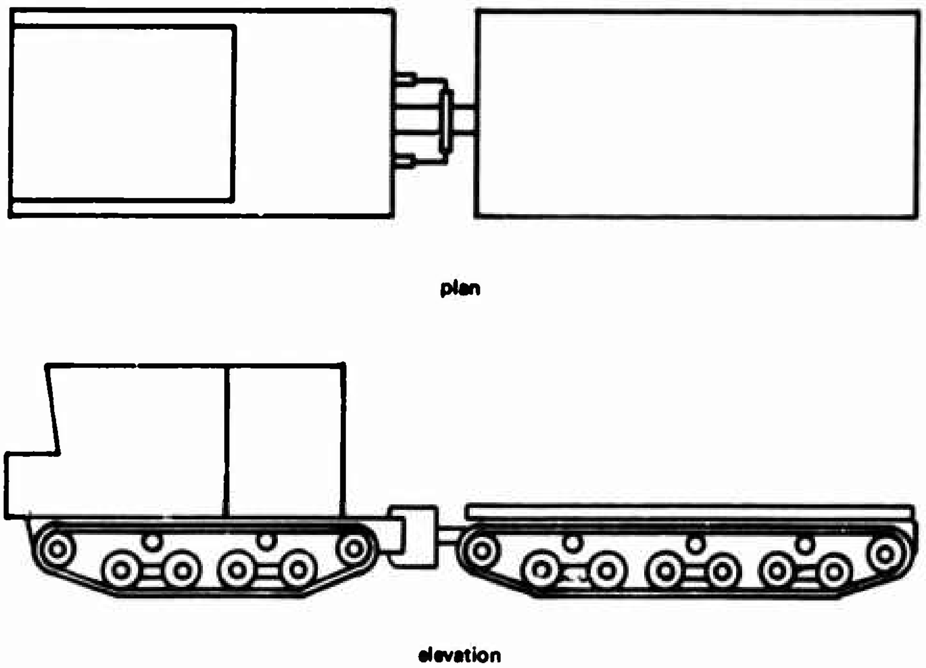

Figure 33. Musk-Ox articulated freight carrier.

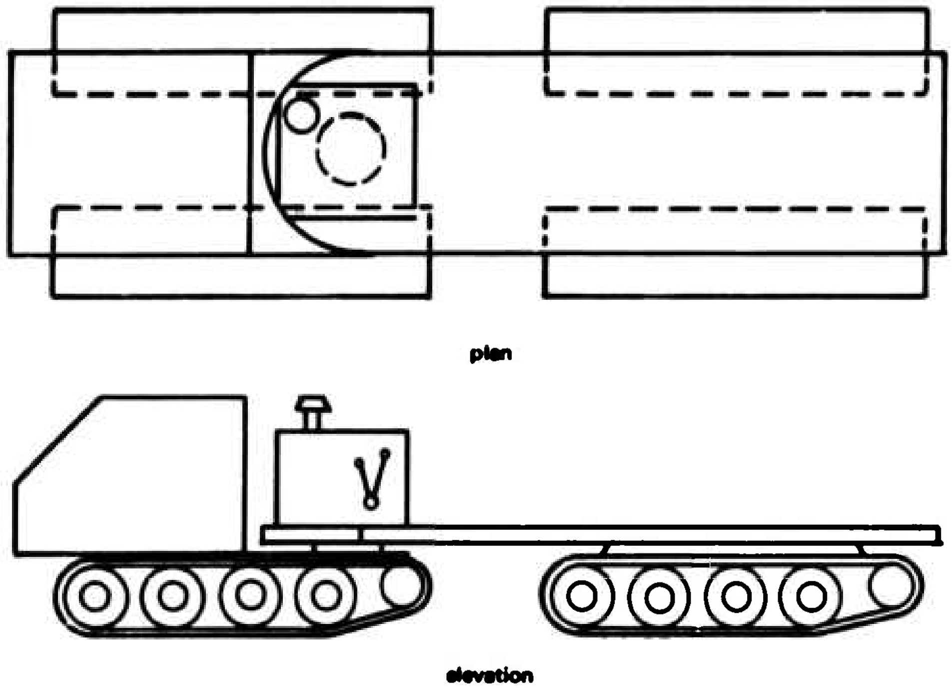

Figure 34. Nodwell articulated freight carrier.

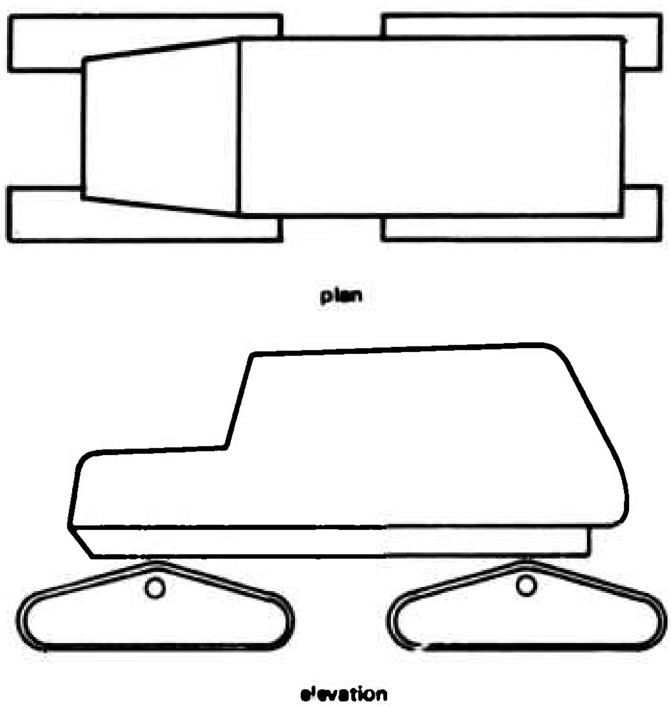

Figure 35. Tucker Sno-Cat.

A vehicle called the Tundra Truck employing the endless belt concept was built by the Laboratory and tested in 1958 and 1959. Each of the two belts was 5 feet wide, had a ground contact length of 28 feet, and was smooth on the outside. There were 200 8-inch-diameter bogie wheels to provide an even distribution of vehicle weight over the belt area in contact with the ground. It was found that the bogie wheels sank into the rubber belt approximately 5/64 inch, creating excessive rolling resistance. In addition, the length to gage ratio of the belts was 2.71 which made steering impossible. It was felt, however, that even if the length to gage ratio had been below the 1.9 maximum, the vehicle would probably have had trouble in turning. When it was towed by a tractor and subjected to a side force, the tracks continued in a straight line and the body moved sidewise causing the drive rollers to roll out of the rubber tracks, wedging the tracks against body members.

The vehicle ground bearing pressure was 1.6 psi. On soft mud the belt left a flat smooth track, but mud squeezed up on the sides and between the tracks and got into the bogie wheels increasing the rolling resistance. In addition, a wave of mud formed in front of the tracks due to the bulldozing effect. This added resistance stalled the vehicle.

The rubber belt concept, as developed so far, appears to be unsuitable for use in soft muds such as are found on the ocean bottom.

Low-Pressure Tired Wheel. In applications where they can be used, wheels have several advantages over tracks: low maintenance costs, low rolling resistance, easy steering, and high speed. On the other hand, they must be extremely large to provide a very low ground bearing pressure. In soft terrain, they tend to bulldoze soil. Several low-pressure tires have been developed for the purpose of providing low ground pressure or "flotation" for vehicles traversing snow, mud, and other surfaces where conventional wheels cannot operate. In deep water, however, due to the high pressures, the use of an air tire would be complicated by the necessity of inflating it at the work depth. It could be filled with fluid but this would eliminate its ability to provide buoyancy, which may be needed.

The Terra Tire, made by the Goodyear Tire and Rubber Company, is an example of the low-pressure tire. To provide a large bearing area without enlarging the wheel diameter beyond practical limits, the Terra Tire is lengthened along its axis of rotation so that it is about six feet wide and four feet in diameter. From the front, it looks like a large, soft roller rather than a tire. Although this provides the required low ground pressure, it violates the second requirement for a successful snow vehicle mentioned earlier, that of a long, narrow bearing area. It has been previously pointed out that rolling resistance due to bulldozing is proportional to tire or track width. For a given ground contact area, the wide tire has an unfavorable rolling resistance. Terra Tires are now made in a variety of widths and tread designs for different applications. Some of them have been successful on soft, wet soil and snow.

Goodyear's Liquid Transporter and the Rolligon air bag made by the Albee Rolligon Company, Incorporated, are similar to the Terra Tire. These units are made of soft, light materials and tend to "flow" over the ground in a manner similar to the flow of a viscous liquid, conforming to rocks and other hard obstructions as they pass over them. They must be driven from the periphery, however, as the soft sidewalls will not transmit power from the axle. A powered roller, bearing against the tire periphery, transmits power to the wheel by friction. On the ocean bottom, the coefficient of friction between the roller and the wet rubber tire, especially in locations where they would be lubricated by a film of clay adhering to the tire surface, would be so small that practically no power could be transmitted in this manner. For this reason, they would probably be impractical for use under water, except on a towed vehicle. A Rolligon equipped vehicle has been tested on soft snow and found to be unsatisfactory (Mellor, 1963).

Oblate Wheel. An oblate wheel was laboratory-tested at NCEL in 1951 (Weiss and Magill, 1951). This model measured 10.6 inches on the long axis and 7 inches on the short axis, and was 1-1/2 inches wide. It was concluded that this wheel was superior to a round wheel in wet and dry sand and would probably be superior in mud and snow. It tended to roll itself out of its own rut, rather than having to plow through the soil. It appeared that the long axis of the wheel penetrated deeply enough in the soil to develop shear deep in the soil mass, going far beyond the contact surface between the wheel and soil (Figure 36). Greater drawbar pulls were developed by the oblate wheel than by a conventional round wheel of the same circumference. This wheel has not been tested operationally on a vehicle, but it might prove useful on the ocean bottom.

Archimedean Screw. Much time and effort have been expended to develop a vehicle based on the Archimedean screw for traversing snow, mud, and swamp areas. Generally, the concept employs two buoyant cylindrical pontoons with conical ends (Figure 37). Encircling the sides of the pontoons is a narrow fin in the form of a screw thread around the cylinder; a left-hand thread on one pontoon and a right-hand thread on the other. The passenger, cargo, and engine space is between the two pontoons. The pontoons float on the mud or snow surface, and the counter rotating screws propel the vehicle.

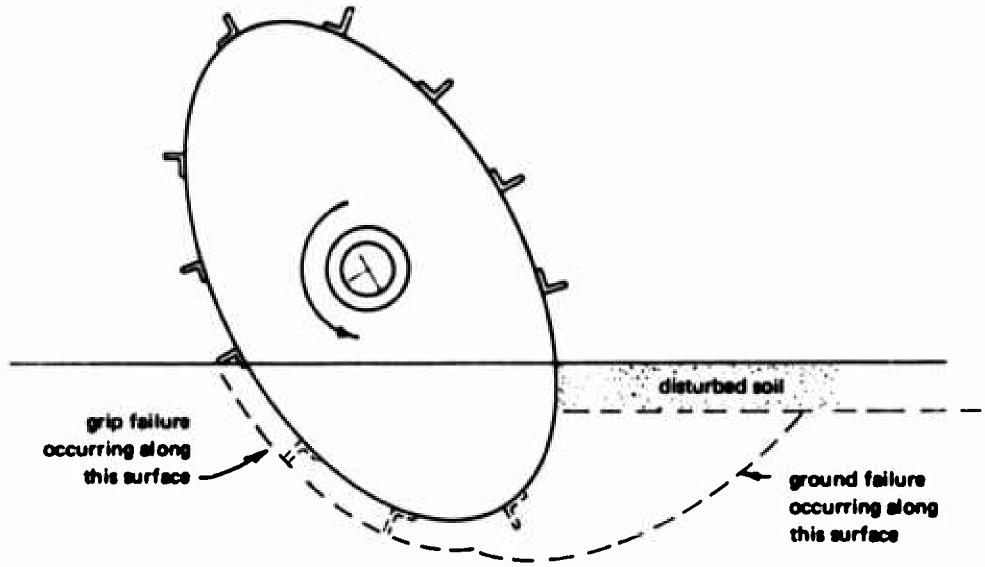

Figure 36. Tractive behavior of oblate wheel.

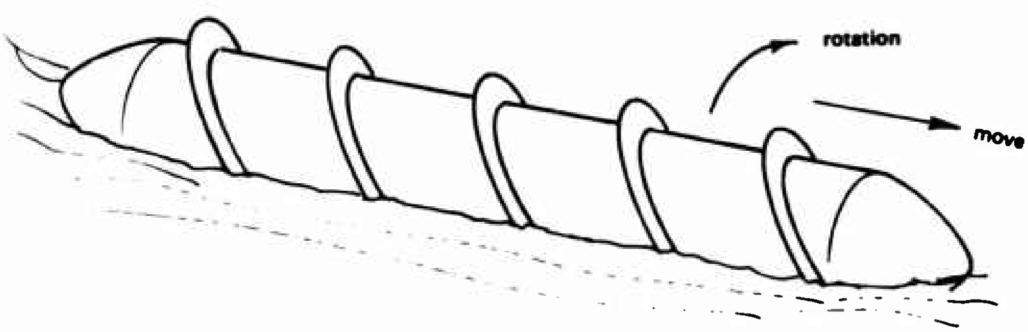

Figure 37. Archimedean screw pontoon.

This concept has been used with a fair degree of success on a small snow "scooter" but, inspite of extensive developmental work, has not proved practical for a passenger or cargo vehicle on land (Beck, 1957). For the ocean bottom application, however, it may be worthy of consideration. Tests at the Waterways Experiment Station (WES), Vicksburg, Mississippi (Knight, Rush, and Stinson, 1965), revealed that the Marsh Screw, and Archimedean Screw vehicle, could operate on extremely wet, soft soils where other vehicles of equal size and weight could not. If the soil had free water on its surface or contained large amounts of free water in the top few inches, the Marsh Screw performed quite well, almost unaffected by the soil shear strength. The critical factor apparently was the friction between the soil and the rotors. On wet or dry sand and on sticky, water-free soft soils, the Marsh Screw was definitely inferior to the M29C Weasel, a tracked vehicle.

Walking Barge. The Walking Barge was built as an amphibious cargo carrier and tested at NCEL shortly after World War II. This large floating barge was divided longitudinally into three segments or pontoons, the center one with a bottom area equal to the sum of the bottom areas of the two side pontoons. When the barge was driven ashore and grounded, it proceeded up the beach by resting on the center pontoon, moving the two outside pontoons up, forward, and down until the weight was transferred to them. Then the center pontoon moved up, forward and down to complete the walking cycle. This was repeated to provide forward motion over the beach (Figure 38).

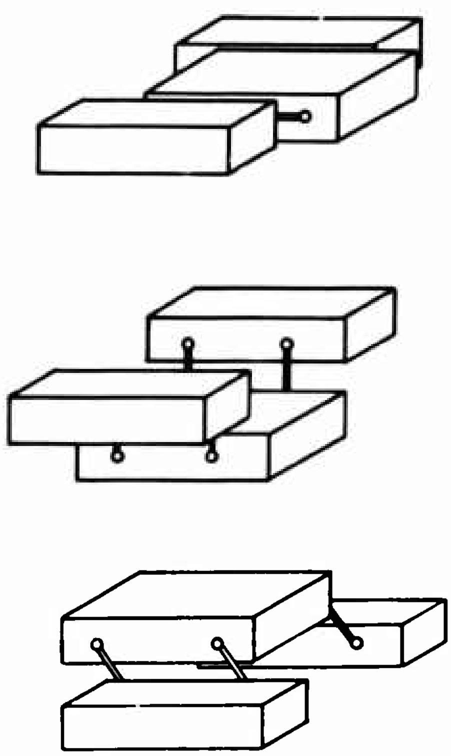

Figure 38. Walking barge principle developed at NCEL in early 1950's.

At first glance, an apparent advantage of the walking barge was its large, flat bottom which provided a large ground contact area and low ground pressure. In operation, however, all the weight was usually transferred to one-half the bottom area, thus doubling the apparent ground pressure. On a sandy beach, this was no problem, and the barge moved steadily forward.

In tests on the mud flats at Point Mugu, the walking barge sank several feet into the mud but stayed afloat and moved slowly forward. After a few dozen feet of progress, however, the weight-bearing surface sank so deep in the mud that the other pontoon, or pontoons, dragged in the mud surface on their forward travel; this counteracted the rearward drag and caused the unit to stop its forward movement. It was proposed to put hinged flaps on the bottom of the pontoons which would fold flat against the bottom during the pontoon's forward movement and drop down into a vertical position during the pontoon's stationary period to prevent their slipping backward. This proposal was never carried out.

Tractive Effort

The force developed in the soil to propel a vehicle is called tractive effort. This force is made possible by the shearing strength of the soil (Bekker, 1956, p. 255).

In Equation 8, it was shown that the soil shearing strength, **s**, is equal to the soil cohesion, **c**, plus the normal pressure of the shear plane times the tangent of the angle of internal friction, ϕ:

$$s = c + p \tan\phi \quad (8)$$

The shear occurring at the ground contact area between the soil and a vehicle, at the point close to a stall, is a large-scale replica of the shearing process produced in the laboratory by means of the shear-box under the conditions expressed by the above equation.

Figure 39 shows this analogy and implies that the horizontal tractive force, **H**, and vehicle weight, **W**, acting upon the ground may be related by the same equation as above,

$$H = Ac + W \tan\phi \quad (12)$$

where **A** = the shear area, which is approximately equal to the track ground contact area.

In a purely frictional soil such as dry sand, **c** = 0 and the tractive effort becomes

$$H = W \tan\phi \quad (13)$$

In this case the tractive effort is proportional to vehicle weight, **W**.

In a purely cohesive soil such as soft, saturated clay, however, where ϕ = ` we have seen that **s** = **c** (Equation 9) and only the soil cohesion contributes to the shear strength. In this case, the tractive effort becomes

$$H = Ac \quad (14)$$

Here the vehicle weight does not enter the formula and the tractive effort basically depends only on the ground contact area, **A**. Thus, the criterion for track design for use on the saturated plastic soils found on the ocean bottom, is track size: the larger the ground contact area, the better the traction.

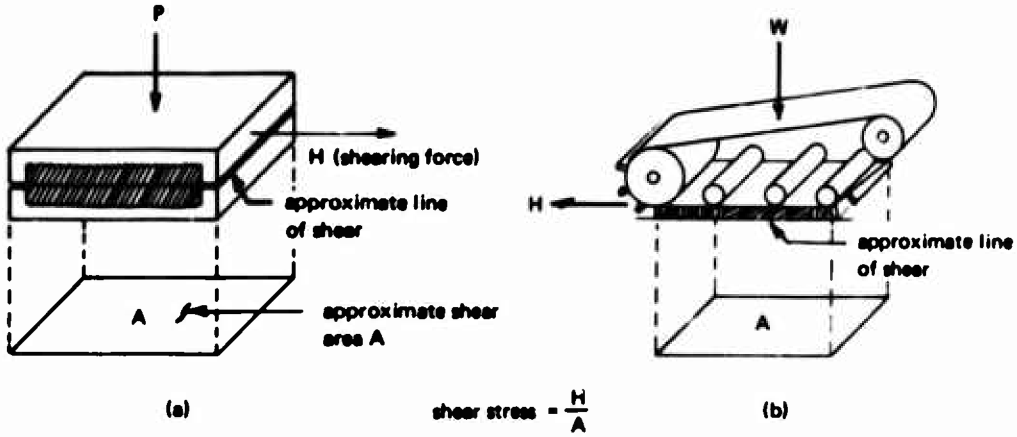

Figure 39. Graphical analogy between laboratory soil shear box (a) and a track on undisturbed soil, (b).

It is extremely difficult to predict the traction that will be available in a saturated submerged soil. Although the shear strength of an undisturbed soil sample may be determined, the effect of agitation caused by a vehicle moving through the soil–water interface is to mix the soil and water. In the case of soft clays whose particles are very small and light, the whole mass of disturbed soil can be mixed with the water and become liquid. In this state, the cohesion is destroyed and no traction will be available. Hydromechanical methods may then be the only means of locomotion under these circumstances (Bekker, 1956, p. 142).

Propellers produce thrust, or tractive effort, by changing the momentum of the fluid in which they are submerged. A vehicle working on the ocean bottom using propellers for propulsion would not have to depend on the highly unpredictable bottom soil for movement. Another advantage of a submerged propeller is that it can be made to produce a dependable amount of thrust in any direction, including the vertical.

Another hydrochemical device for producing thrust is the water jet. This is essentially a pump that creates a water jet and by so doing has a thrust exerted upon it which is the propelling force. In fact, a propeller does the same thing and thus is one form of water jet propulsion (Streeter, 1948, p. 114).

The propelling force, **F**, of a water jet unit is

$$F = \rho Q \Delta V \qquad (15)$$

in which ρ is the fluid density, **Q** is the quantity of fluid moved in cubic feet per second, and ΔV is the absolute velocity of the fluid.

It can be shown that the theoretical mechanical efficiency, e_t, of a water jet system is the same as that for a propeller and can be expressed as

$$e_t = \frac{1}{1 + \frac{\Delta V}{2 V_1}} \tag{16}$$

where ΔV is the absolute fluid velocity in the jet and V_1 is the speed of the boat or vehicle being propelled.

Other things being equal, $\Delta V / V_1$ should be as small as possible. This indicates that the water jet is most efficient on a high-speed boat where V_1 is large. For low speeds, however, V_1 must be very small. At any given speed, the resistance force, F, is determined by the body and the fluid in which it moves; therefore, in Equation 15 for ΔV to be very small, ρQ must be very large. For this reason, a water jet unit on a slow moving vehicle would require a very large jet with a low velocity discharge. The type of pump best suited for large flow at small head is the axial flow propeller pump. In effect, a propeller is an axial flow pump with the pump casing and jet pipe removed. Therefore, for a slow moving underwater vehicle, propeller propulsion would be more efficient and lighter than a comparable water jet propulsion system.

A water jet system can be justified for slow moving craft in applications where a propeller would be vulnerable to damage from collision or grounding. In the deep ocean, however, there is no reason why propellers could not be mounted above the deck or protruding from the sides of the craft where they would not come in contact with the bottom.

On tugs and towboats where high thrust at slow speed is required, the Kort nozzle is very effective. This is a nozzle or ring of airfoil section in which the propeller rotates. In effect, it provides a cross between a propeller and a large discharge area water jet. It has the additional advantage of providing a protective ring which may assist in keeping foreign objects such as ropes or cables from becoming entangled in the propeller.

Summary and Future Plans

It is apparent that probably no one traction method will function on all possible ocean bottom materials. On solid or rough surfaces, large tires should prove most practical. For most soft bottoms typical of the deep ocean, tires will not be functional, and some form of low-ground-pressure track will be necessary. Interchangeability of tires and tracks on the same machine may prove the best approach.

Of the track systems, the low-ground-pressure pontoon with a ladder grouser system is predicted to be the most successful, and will be functional on all but rocky bottoms. Ground pressure can easily be adjusted to the soil conditions using buoyancy.

During the preparation of this report, a single test track conforming to the conditions listed in the summary was designed and fabricated; the schematic from the contract proposal is shown in Figure 40.

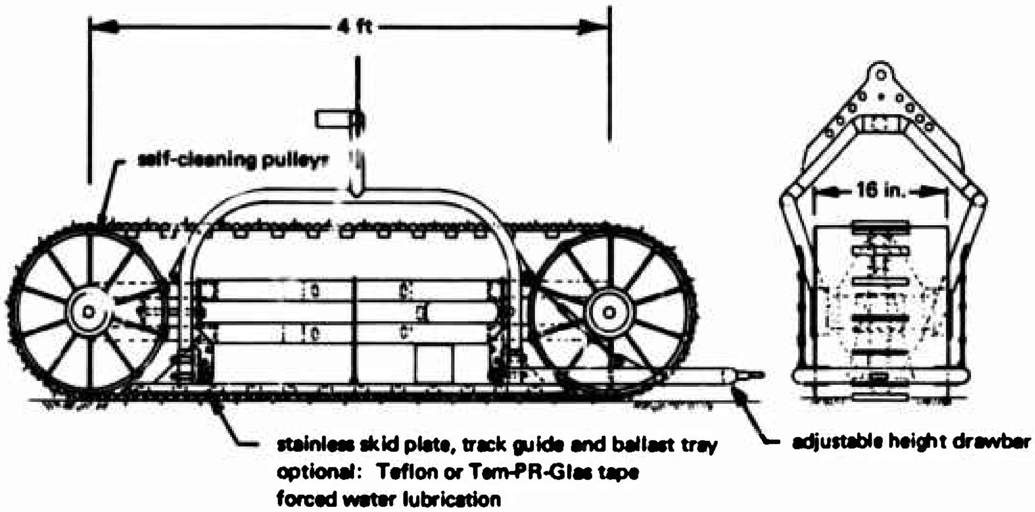

Figure 40. Experimental test track with water lubricated rubber belt sliding on stainless steel skid plate (Nuttall, 1970).

The actual equipment is shown in Figure 41, suspended prior to tests in shallow water of Chesapeake Bay, Maryland. Results of these early tests are described in Nuttall (1970a) and in Nuttall (1970b). The unit is being tested extensively in submerged bottom materials by the Naval Civil Engineering Laboratory, with results expected to be published in a technical report by or before mid-1971. Preliminary analysis of results indicates that for bottoms other than sand, the maximum traction that can be achieved can be developed at low ground pressures and essentially zero slip, and that higher pressures and greater slip than these minimum values tend to destroy the structure of the bottom material. The tracks then dig in rapidly, an undesirable consequence. The cleated track is carried on a rubber belt which is in contact with the smooth steel bottom. A novel feature of this design is that water can be forced under low pressure between the track and the belt, resulting in a very low friction. The unit, hydraulically powered, is to be tested in a variety of conditions including shallow water in muds, sands, and loose sediments. Provision is made for adjusting the ground pressure and measuring the drawbar pull developed. Optimum use of buoyancy to adjust the total ground pressure will be incorporated in the final designs.

Figure 41. Test track described in Nuttall (1970a) in water at Chesapeake Bay, supported between the pontoons of WNRE's test rig.

BUOYANCY SYSTEMS

The ability to employ suitable buoyancy to support large weights in the ocean is probably the single greatest plus in working there over terrestrial locations. On the surface, simple open hulls are sufficient. At shallow depths, either a pressure-resistant hull or a filling material (probably air) at the local pressure of operation or higher must be used to prevent collapse. At successively greater depths, either the pressure-resistant shell must be made stronger and heavier or the pressure of the gas must be increased. Spherical aluminum floats are used to a few thousand feet, at which point the shell thickness necessary is such that the net buoyancy is greatly reduced and the buoys are no longer economically attractive. Spherical and cylindrical shapes typically fail in buckling from instability rather than by compression when made of ductile materials. Nonductile materials and those of comparatively low strength perform well over certain pressure ranges, particularly if the density of material is low enough to allow thick walls, which are stable against buckling. Glass is a particular case of a very strong, nonductile material which actually increases in strength when under compression over practically the entire pressure range to be met in the world's oceans (Perry, 1963).

While concerted efforts along the lines outlined above are being made under other assigned portions of the Deep Ocean Technology project and other ocean-related research and development tasks, it does not appear that economically feasible developments will immediately be ready for use. Because large volumes of relatively low-cost buoyancy materials capable of withstanding full ocean pressure will be needed to build an adequate low-ground-pressure chassis for soft bottom materials, a limited effort in development is outlined here. Features to be sought in order of their importance are:

1. Low cost per unit buoyancy
2. Pressure resistance of completed buoyancy units
3. Low density
4. Ability to withstand rough usage as fabricated
5. Low thermal coefficient of expansion

The so-called syntactic foams, in which very small beads of either glass or a strong plastic are embedded in a strong plastic binder such as epoxy, have been widely used in small systems and considered for at least one large application (Bechtel, 1965). They are good in factors 2 and 4, but are very expensive and marginal in density and expansion traits. Figure 42 (Bechtel, 1965) illustrates the form and application of massive floats to a buoyancy system for lowering a nuclear reactor to the ocean bottom.

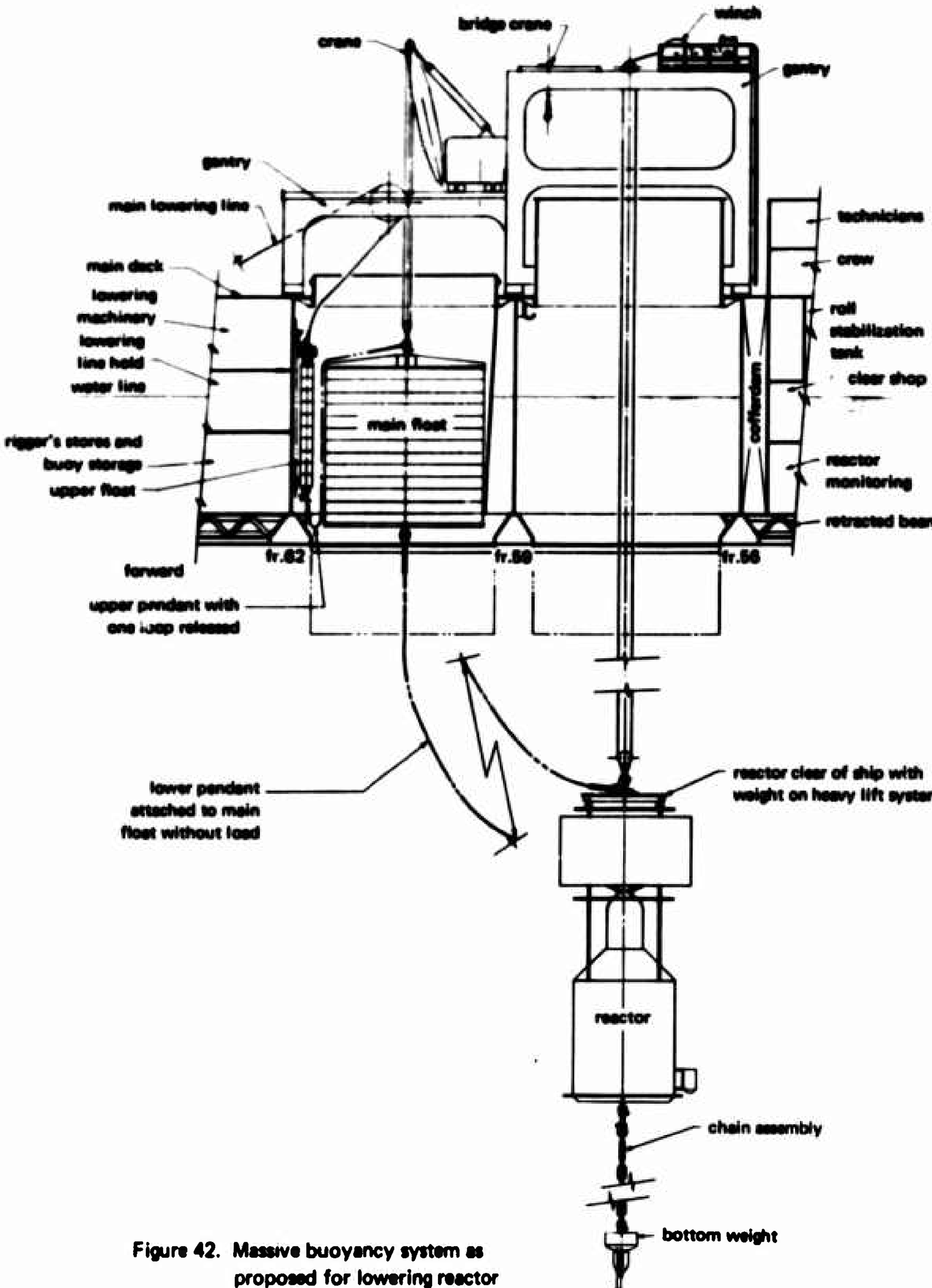

Figure 42. Massive buoyancy system as proposed for lowering reactor in ocean (Bechtel, 1965).

All of the above factors but the last may be obvious; a low coefficient of expansion is critically necessary to keep the total buoyancy system simple. If the buoyancy material changes volume drastically with depth for any reason, then the buoyancy will not be constant. If the modulus of compressibility is low, the net buoyancy decreases rapidly with depth. Acting in the same direction would be a loss in volume with cooling, which can be expected to be an important factor in all but polar seas. Whatever the surface temperature of the water, in most situations the deep water will be colder, and flotation materials will lose further buoyancy on cooling at the bottom. This may take considerable time but will eventually occur. Some form of trimming control on the bottom might be necessary but would be complicated. An alternative which is only slightly less attractive would be to precool the mass by soaking in a cold bath at the surface.

A method of improving wood to obtain the desired strength characteristics for fabricating buoyancy shapes has been proposed (Beck, 1967), but to date the necessary development and testing has not been done. Of the 13 references in the proposal, the most important for discussion are Barnes (1964) and Kukacka and Manowitz (1965). The former gives an excellent condensed account of the status of wood as a production material. The latter discusses the change in compression strength and hardness which may be accomplished by impregnating hard woods with highly penetrating monomers and then irradiating them with gamma radiation. Figure 43 (Barnes 1964) shows a greater than two-fold increase in strength with heavy impregnations.

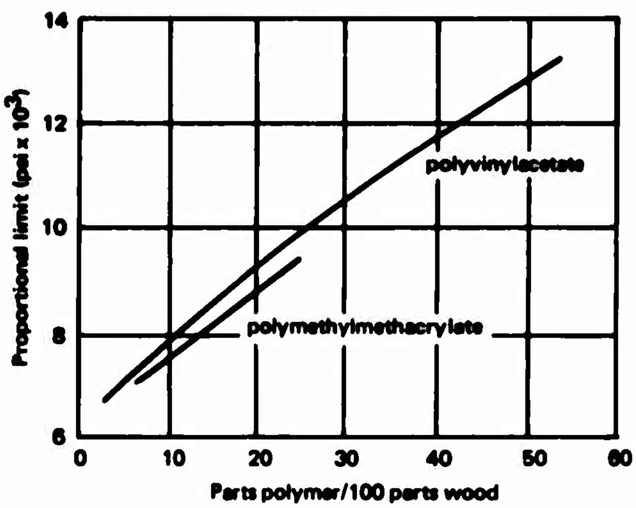

Figure 43. Compressive strength of sugar maple filled with plastic monomers and polymerized by gamma radiation (© Barnes 1964. Used by permission of Machine Design.)

A less costly concept for employing wood in buoyancy shapes is illustrated in Figure 44. Typically the compressive strength of timber perpendicular to the grain is many times less than that parallel to the grain. For coast-type Douglas fir at 12% moisture content, for instance, the relative values are 870 to 7,430 psi, respectively, a ratio of over 1 to 8 (USDA, 1955). This suggests the fabrication configuration shown in Figure 44, in which the fibers are selectively oriented to take advantage of the anisotropy. This relatively inexpensive wood with minimum waterproofing of sheathing should be useful at least 12,000 feet in the ocean. Other even more advantageous arrangements could probably be developed. For one thing, it appears that some collective reinforcement should be possible with suitable preferred fiber orientations, so that the measured stiffness in the complex structures would be greater than calculations based on individual components. This phenomenon is referred to as "jamming."

A recent development in buoyancy, not yet fully tested in a pressure environment, is described by Madden (1970). Figure 45 from that source shows closely packed spheres formed from brazed hemispheres in a possible replacement for the well-established honeycomb core material developed for industrial and aerospace applications. The material offers promise both as a buoyancy and a structural material.

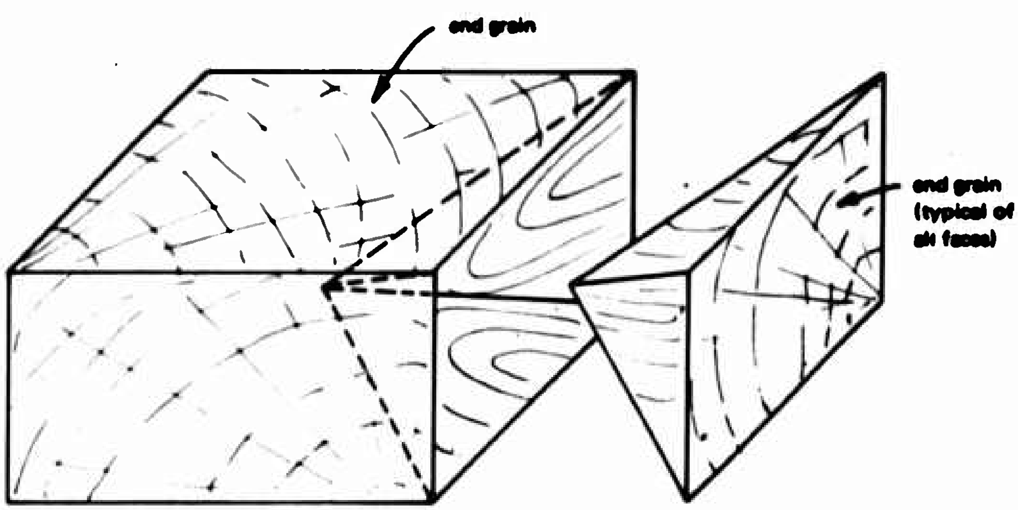

Figure 44. Composite wood buoyancy shape, with end grain exposed on all faces for greater strength.

NOT REPRODUCIBLE

Figure 45. Top view of expanded sphere core structure prior to tests.

Useful, inexpensive, and simple static buoyancy systems appear easily achievable for the short-term development of a low-ground-pressure or buoyed chassis for bottom drilling and excavation. For the long-term development program for depths to 20,000 feet, added complications in the form of adjustable buoyancy appear to be justified if it can be developed. One possible approach is described in a proposal (Beck, 1964), in which the goal would be the development of an active system capable of keeping a massive system at a predetermined level, constantly adjusting buoyancy to achieve this. Some formidable obstacles can be anticipated, not the least of which is the continuous power drain. Small submersibles represent a compromise in the combination of vertical propellers, deballasting and ballasting (compressing a ballast tank partially filled with gas by pumping in seawater), and use of forward motion reacting against horizontal hydrodynamic surfaces. For the massive earthmoving systems envisioned here, the problems appear to be less awesome. Vertical accelerations would be less, both because of mass and extended horizontal surfaces. Power intrinsic to the operation of the machinery would always be available in large quantity, unlike the situation in small submersibles and in the Buoyancy Transport Vehicle developed by the Navy Undersea Research and Development Center, Hawaii. Both of these applications use batteries for power and extensive use of power for ballast control will limit their range.

A final vertical stabilizing influence arises from the proposed vehicle's purpose—bottom work. The forceful contact with the bottom suggests that flotation trim will not be critical so long as some portion of the vertical force is taken in the tool contacting the bottom.

It may well prove that for many bottoms, shear strength will be so low as to negate the effectiveness of wheels, tracks, belts, etc.; in those cases, a barge "floating" at the water–bottom interface and reacting through a propeller in the water above would afford the necessary lateral movement (Figure 46).

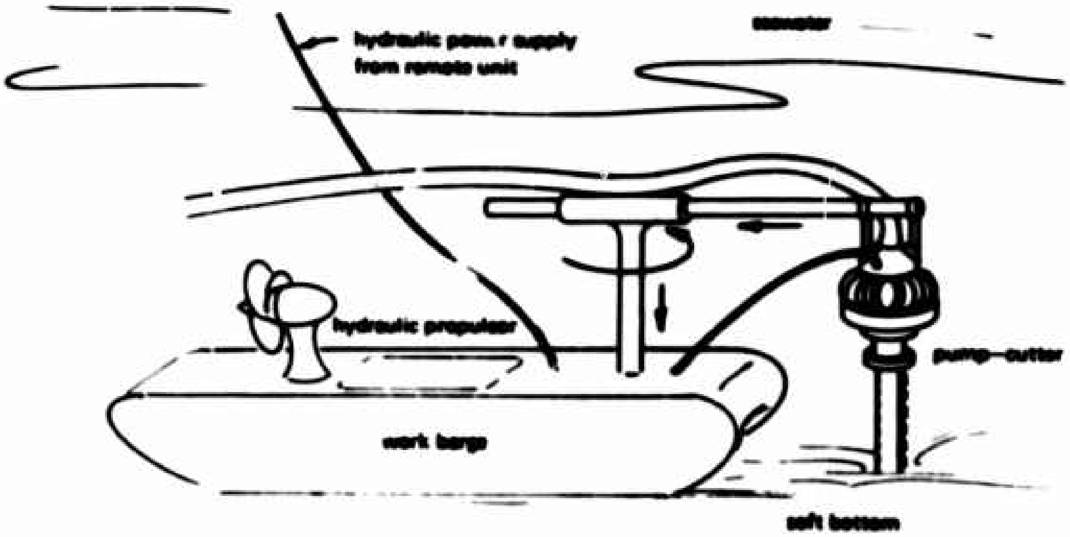

Figure 46. Concept of a barge-mounted work system for local excavation.

Summary

Adequate pressure-resistant buoyancy systems are available, but costs for depths to 20,000 feet are inordinately high, suggesting investigation of new approaches such as beneficiated wood.

Future Plans

No active research and development are planned in the area of buoyancy, except for limited, informal small-scale pressure chamber trials of a few simple systems for impregnating and sheathing wood.

SHALLOW DRILLING AND EXCAVATING

The operations described in this section are those which in surface operations normally would be done by bulldozing, scarifying, scraping, shallow auger drilling, and loading and removal of the spoil from the site, or using it for backfill. These are all specific operations requiring great operator skill and, to achieve accuracy, repeated checking of grade, tamping, etc. There is at present no reasonable hope of performing these same functions on the ocean bottom in the same manner. Fortunately, there appears to be no need to use established terrestrial methods.

The precise excavation foreseen as necessary for ocean-floor sites will be largely accomplished by a machine that will function similarly to a numerically controlled milling machine (Figure 47). However, instead of moving the workpiece below the mill with respect to a stationary cutter, it will be necessary to move the milling head with respect to a movable platform (Figure 48),* or with respect to a fixed clump (Figure 49). Where preparation of the immediate area is needed for installation of a prefabricated structure or other assembly, the massive clump would be lowered with the earth-milling equipment in place. Upon completion of the excavation phase, the machinery would be detached and raised to the surface, leaving a precisely formed area to accept the permanent installation.

In conventional metal milling (Figure 47) cuttings are flushed away or removed by hand. Soil or rock cuttings, on the other hand, will be immersed in water and relatively finely divided. It remains only to cut them in such a way that they can be sucked into the rapidly moving fluid stream and pumped either into a fast moving current or to a site away from the operation, where they will form a harmless sediment. Use of water for spoil removal is the big plus in underwater operations.

At least two evident mechanisms for traversing the cutting head or mill over the work area are available (Figure 50a and 50b). In the arrangement of Figure 50a, the cutter would be traversed over an area ahead of the supporting barge by movement of tubular ways. A second set of ways would traverse it at right angles, and the vertical movement would be accomplished through a vertically moving column bearing the mill, pump and hose as necessary. This would be essentially duplicating the motion of the ways and milling head of a vertical mill (Figure 47). From a control standpoint, it would be desirable to use this arrangement. The standard programs and control techniques for numerically controlled machines could be used with little modification with such a machine in conjunction with three-dimensional rectangular coordinates.

Development of suitable controls for the type of machine illustrated in Figure 50b, on the other hand, would probably require greater effort, as instructions would have to be translated from the normal engineering rectangular coordinates to a combination of polar coordinates in the horizontal plane and a linear coordinate in the vertical, resulting in a combination which might be called cylindrical coordinates. Mathematically, this is not difficult, but the change does introduce one additional step in instructing the machine. The resulting machine would be mechanically far simpler than that diagramed in

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* See also Figure 46 and related text.

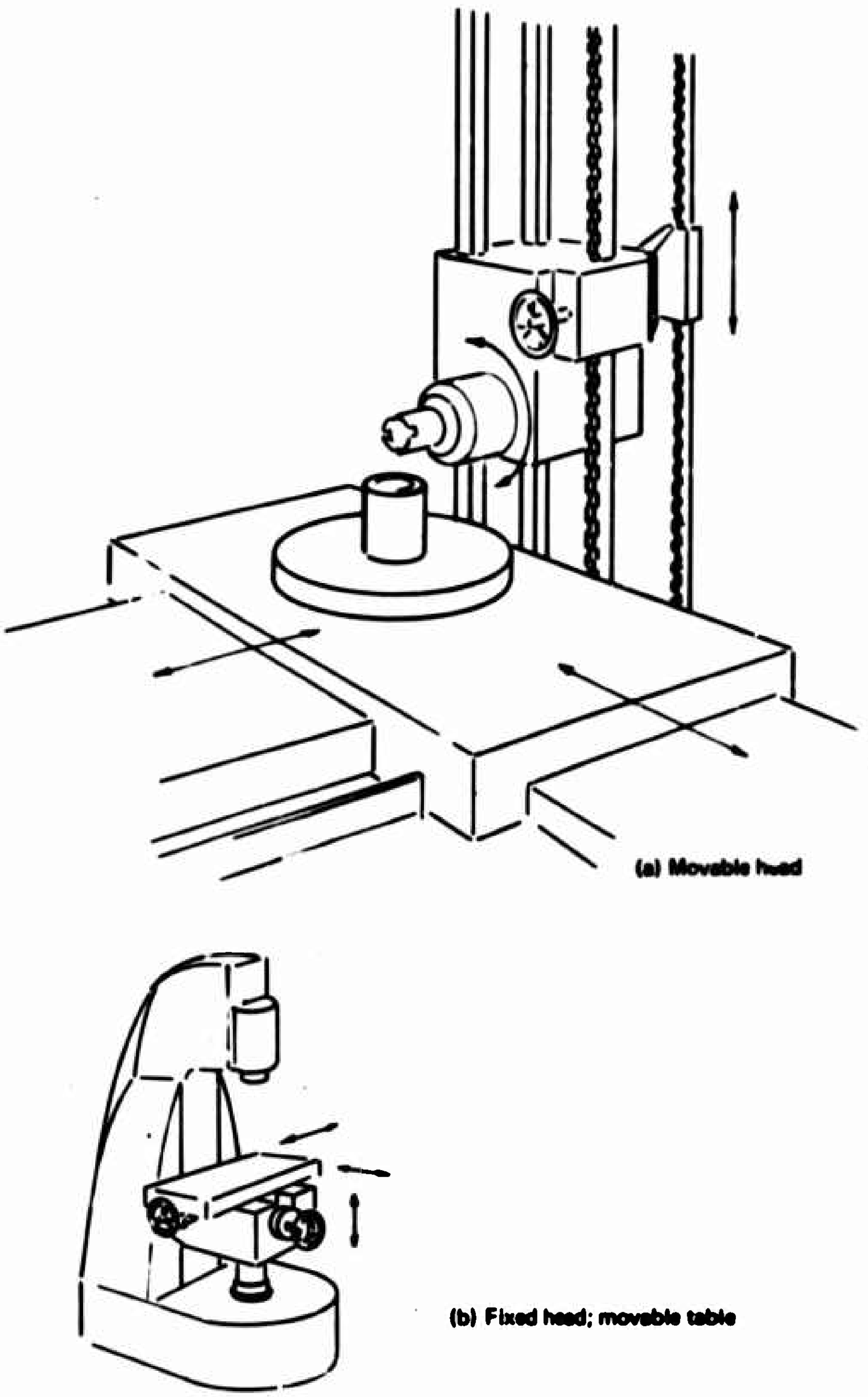
Figure 50a, and more flexible. It would not require accurate alignment to the work site as would the more complicated machine, because its control system could be indexed to compensate for angular displacement of the chassis from the desired geographical direction. It could work all around itself, giving a much greater working area without relocation, simplifying the control problem further.

An additional simplification in machine development would be accomplished by adapting a commercially available hydraulic crane as shown in Figure 51. However, the control problems would be further complicated in that this machine would use full polar coordinates—it would see the world as a sphere. Within limits it would be able to excavate even under itself.

The preceding discussion of the earth milling (or controlled dredging) concepts by no means proposes to eliminate the possibility of adapting conventional earthmoving techniques and machines to the ocean floor. At least one remotely controlled bulldozer is known to be available from Japan (Anonymous, 1968). It would be comparatively simple to power a small bulldozer with individual hydraulic motors (Nuttall, 1970a) on the tracks. The combined problems of turbidity during the work period, inaccessability for control, and the inability to drill shallow holes for piling, etc. inherent in conventional earthmoving makes this approach relatively unattractive in comparison to milling. Bulldozing is a cut-and-try process relying heavily on the operator's abilities and the making of successive cuts to achieve grade. The potential for simple and accurate profiling is obviously not there.

It is a major thesis of this study that accurate profiling of work site to accept the prefabricated structures is needed for installation of prefabricated installations. In the realm of manufacturing, this type of control is routinely and precisely obtained with such machines as mills and surface grinders. In particular, the numerically controlled vertical spindle mill is a highly controllable, mechanically simple machine capable of intricate profiling, limited only by the sophistication of controls. The previous discussion provides an outline of the proposed approach for achieving the same capabilities in machining the surface of the ocean bottom. Numerical or computer control according to a preplanned profile makes accurate profiling possible in a remote location without visibility during excavation.

On the basis of early stages of the study reported here, a contract for a systems analysis and preliminary design of a remotely controlled seafloor excavation machine was let in mid-1969 to the Northrop Corporation. The report of the work accomplished under this contract will be issued in early 1971.



(a) Movable head

(b) Fixed head; movable table

Figure 47. Milling machines—illustrating degrees of freedom in movement similar to those required in seafloor milling machines.

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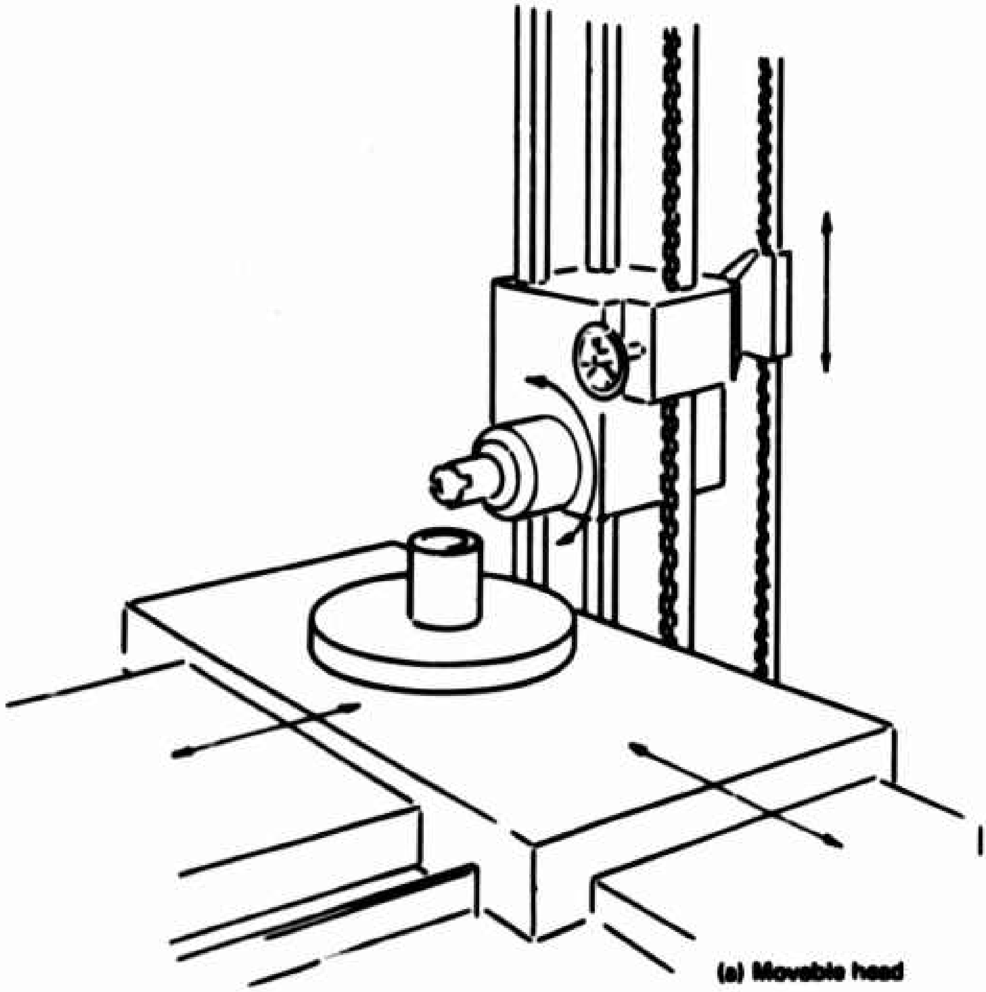
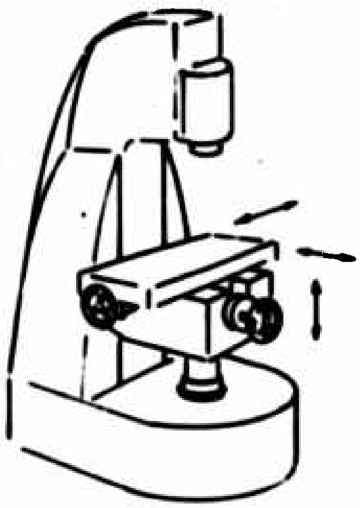


(a) Movable head



(b) Fixed head; movable table

Figure 47. Milling machines—Illustrating degrees of freedom in movement similar to those required in seafloor milling machines.

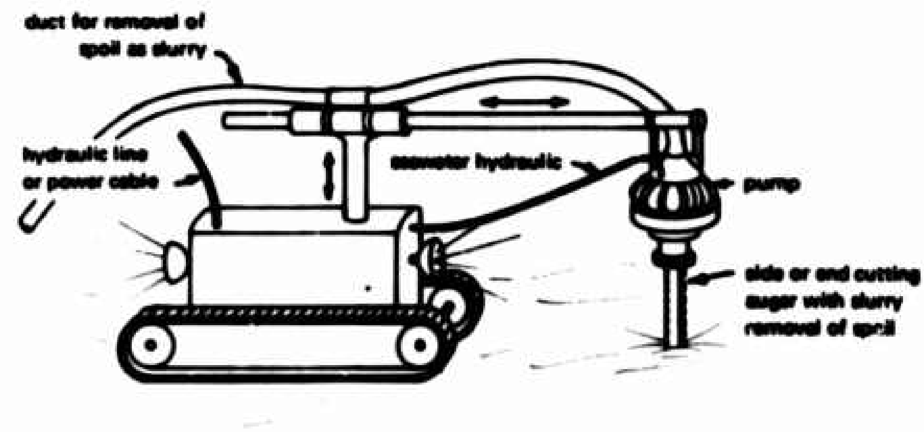


Figure 48. Concept of mobile seafloor excavator.

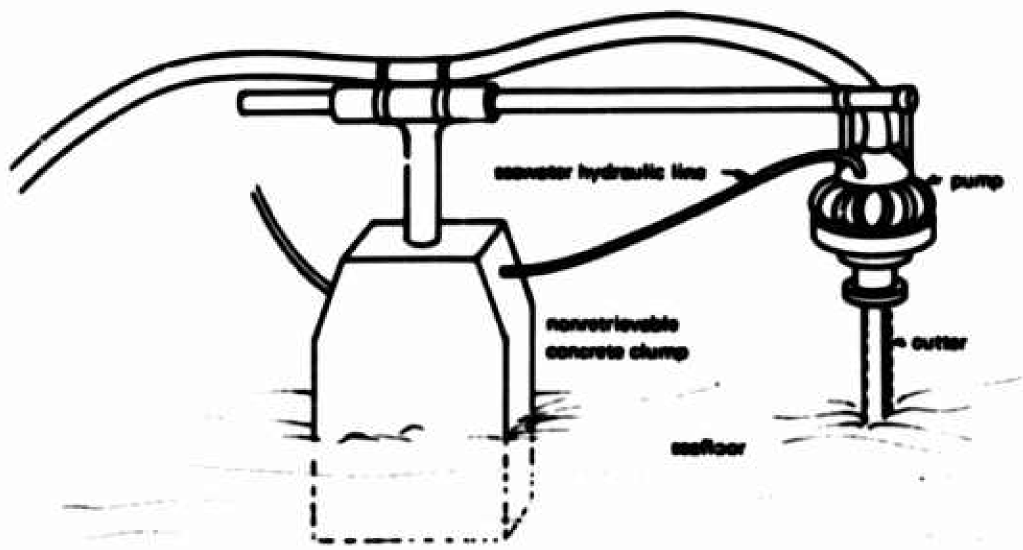


Figure 49. Concept of a fixed seafloor excavator.

A total of eight concepts were identified in the early phase of the work; these were reduced to three in an early trade-off analysis. The three distinct concepts (Figure 52) are: (1) a frame which would require towing and sinking at the work site and which would be capable of very precise proving over a limited area; (2) a rotary machine capable of similarly close-tolerance excavation, but having the added inconvenience of requiring a drilled-in pile and a specialized drilling support ship, of which there is only one; and (3) the concept selected for preliminary design and detailed analysis (right, Figure 52).

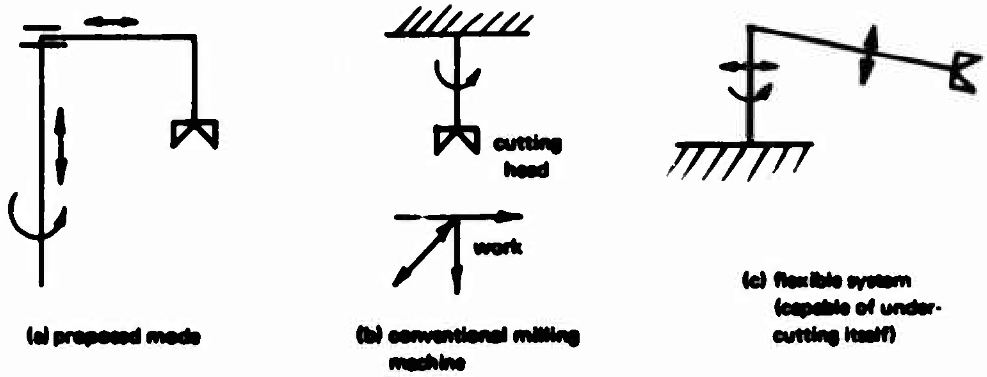


Figure 50. Useful movements in a profiling cutter.

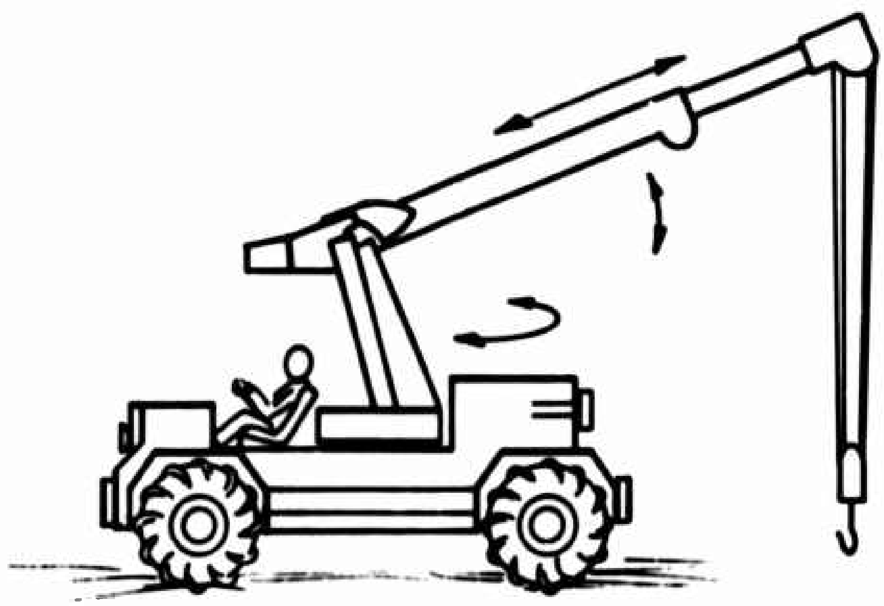


Figure 51. Modified commercially available hydraulic crane suitable for automated polar coordinate controls.

The least conclusive aspect of the entire study and preliminary design was control of the Excavator's cutter head with respect to the ocean's bottom with sufficient accuracy to do useful work. The system recommended in the report for further design, fabrication, and testing would utilize three transponders in an array extending beyond the work site. These would be interrogated by a transducer on the cutter head to permit the position of the cutter to be calculated from the response times by a mini-computer on the surface. The system is described not only in Northrop (1970) but in a paper by Coxe and Buckley (1970).

Figure 52. Three concepts for a remotely controlled seafloor excavation machine; the righthand concept was selected.

Bottom excavation and drilling of soft rocks and most soils can probably best be accomplished with a numerically controlled, independently operating machine with controls similar to those used by a milling machine in metal. The spoil material can best be removed from the work site as a slurry in seawater.

Early future work on this or an alternative concept will probably be concentrated on the positioning and control aspects, both in analysis and in demonstration hardware.

SPOIL REMOVAL

In a typical dry-land excavation or drilling operation, a major part of the equipment, effort, and cost is related to horizontal translatory handling of the loosened material. Exceptions are found on large construction sites where permanent high-volume conveyors can be amortized during a project as, for instance, handling crushed rock in building a dam or on large dredging operations where sand, soil, and rocks are transported either by conveyor buckets or in a pipe as a slurry. Carrying the loosened material or spoil as a suspension in a moving fluid would be economical more often than generally appreciated (Beck, 1968), and the trend to this approach can be seen by the increased activity in development of dredges, semiportable pneumatic systems, and particularly concrete pumps.

The basic problem in handling a broad spectrum of fragmented spoil lies in the cohesiveness of damp soils, high density and variability in rock sizes, and in the low density and viscosity of air the only fluid always available and conveniently usable in most systems. The use of water may frequently be worth considering where it is available, provided the solid medium is amenable to ready separation in simple equipment and provided a body of water can be held at the excavation point. For harbors, mining dredging, and probably many large pit excavations where water is either present in the soil because of a high water table or can conveniently be introduced without endangering the stability of the finished walls, it appears to be a logical medium for rapid and economical movement. Water should become increasingly attractive as a medium for spoil removal when the types of automated equipment and control outlined in previous sections of this report are developed. Where a friable, relatively dry material is being excavated, similar advantages should be readily achievable with air as the moving material. However, for reasons obvious from the following discussion, air velocities will have to be quite high except for any but very finely divided material (see Figure 53). This is not to indicate that the power expenditure necessary to achieve these high

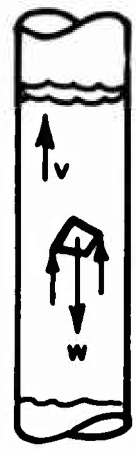


Figure 53. Forces acting on a dense, falling particle in a vertically moving stream of fluid.

velocities cannot be justified with suitable equipment development. The necessary cost-effectiveness analysis for pneumatic systems has not yet been completed, but preliminary estimates indicate that the elimination of high cost labor and loading equipment by use of such a system probably can always be justified.

Sea-bottom excavation presents a uniquely simple case for the use of water for spoil removal. The dense water is a part of the environmental system and it is therefore available in the amounts needed. A brief research of the engineering literature uncovered no theoretical treatment of particle transport by water—and probably for an excellent reason. Referring to Figure 53, an irregular particle of undisclosed dimensions is falling in the conveying medium of density ρ and viscosity μ. If allowed to fall for a considerable distance, the particle will achieve a steady state velocity V, after which it no longer will accelerate. The equations describing the terminal velocity are simple and well known:

$$W = C_d A \rho V^2 \qquad (17)$$

and

$$W = \rho_m v \qquad (18)$$

where W = weight of the falling particle

ρ_m = density of the falling particle

v = volume of the falling particle

A = projected frontal area of the falling particle

C_d = an experimental drag coefficient, a function of shape and Reynolds number

While it would be fairly easy to classify common soils, rocks, etc., according to their probable drag coefficient, etc., the excercise would be of questionable value for two reasons. First, equipment would be typically designed to handle the worst case, and this can easily be determined by observing fall of small rocks of high density and approximately spherical shape. Second, to achieve a dilute suspension and rapid volume movement useful velocities will usually be considerably higher than the minimum for particle suspension. The net flow velocity upward would, of course, be the difference between the fluid velocity and the falling velocity of the particle. The practices in wood particle handling are fairly well standardized. A typical practice is to specify a minimum velocity in a vertical riser and a minimum velocity in a horizontal run. For wood waste the velocity is held between 2,500 and 5,000 feet per minute, with the lower value useful for sawdust and the higher value for heavy chips (Marks, 1958). Similar data are not readily available for water-filled conveyors, but Marks does give a few hints on the design of ash-conveying systems and slurry pipelines for coal.

Tunnel excavators have considered fluid handling of the spoil (muck) as it comes from the working face of a tunnel boring tool. The requirements for rapid excavation with the type of cutters commonly used are incompatible with use of a slurry system. The trend is to develop cutter systems that will produce the maximum size fragments possible, as this generally requires the least power per unit weight of spoil. To successfully move this material long distances through a pipeline requires either (1) finely subdividing the fragments in a crusher to allow use of relatively low velocities or (2) using very high velocities to transport a dilute slurry of the large fragments. Unfortunately, either approach requires many times as much power as the boring machine, the first for crushing, the second for pumping. Nevertheless, this appears to be the only reasonable approach to high production material handling over a long distance which can keep up with advances in the output of tunneling machines (National Research Council, 1968).

Fortunately, the probable material handling rates foreseen for the deep-ocean application are much less than those in surface dredging. Since it will usually be practicable to move the spoil only a short distance, power requirements will be moderate. In developing cutter heads for various kinds of spoils (from oozes to soft rock), fine subdivision to facilitate handling as a slurry in seawater should be kept as a goal. A similar goal should be set for developing rock disintegrating techniques as discussed in this report under "Large Hole Penetration of Competent Rock."

To summarize, slurry-handling systems suitable for spoil removal are in rather broad use industrially, but there is a paucity of technical literature, either empirical or theoretical, on which to base new designs. This is probably because, in dredging operations especially, simple rules of thumb, such as inducting 10 times as much water as spoil, seem to work well. To develop a spoil-milling concept as proposed in this report, some practical experience on a variety of materials should be accumulated in controlled tests of early designs.

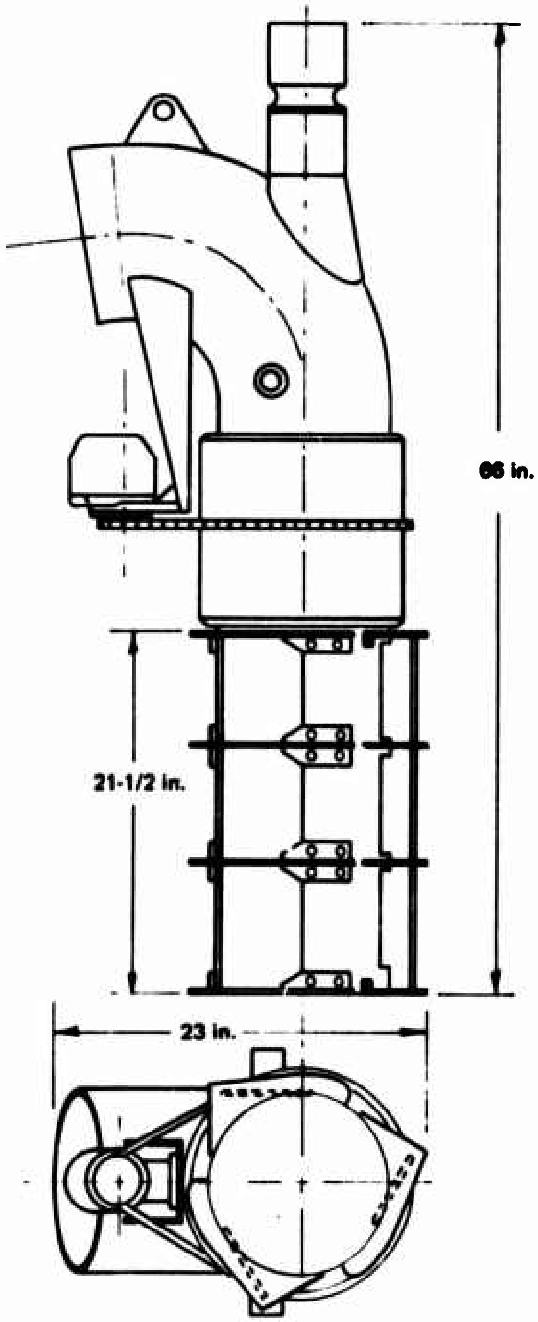


Figure 54. Experimental model of hydraulically powered soil-milling cutter and spoil removal system.

During this study, a combined cutter–slurry removal unit with hydraulic drive was obtained and tested (Figures 54 and 55). The principal information obtained with the equipment shown in Figures 54 and 55 was the lateral force necessary to force a cutter through soil. This would be a particularly important design value in developing a successful mobile excavator as recommended by Northrop (1970). There are no present plans for additional work in this area other than the publishing of the results of this limited but important testing.

REMOTE CONTROL SYSTEMS

This section is based on the earlier discussion of possible machines for excavation presented in the section "Shallow Drilling and Excavating." Because of the high turbidity that can be expected during and for some time after earthmoving and drilling on the ocean bottom, local control of equipment will probably not be feasible. Remote control in itself does not provide the complete answer, either. Preparation of complex surfaces with trenches and holes for piling precisely formed in the surface appears far too complex for a simple remotely controlled machine such as a bulldozer.

The machine proposed for such seafloor site preparation is in essence an enlarged milling machine capable of cutting operations controlled by a tape or other input program. The programed instructions could either be inserted at the surface before the machine is lowered, transmitted sonically once it is on the bottom, or perhaps an optimum combination of the two methods could be used. From a cost standpoint, it appears simplest to preprogram the machine. However, this would permit no change in plans and would require precise positioning. Either a change in plans or imprecise positioning of the machine in the work site would make some sort of corrective action necessary. Several approaches appear possible: (1) use of a telemetry link and reprograming from either a submersible or from the surface on the basis of closed circuit TV information, (2) replacement of the program by a submersible, or (3) orientation correction. (The third alternative would not solve the problem of a plan change.)

The remotely instructed machine performing planned excavation and drilling tasks should take advantage of the latest technology in the automatic machine tool industry. The controlled production machine is a very old concept; probably the first example was the Jacquard loom, controlled by the equivalent of punched cards. Progress has been from punched cards through digital tapes and more recently to direct computer control, using a formal machine language. This approach is seen to have the greatest potential for the application considered here, with the most sopnisticated systems being able to read a simple blue print of the site plan and perform the various necessary operations in a planned routine. For instance, a complex site might consist of a series of foundation trenches, a level table area and a series of holes for pipe pilings. The machine might level the site first, then automatically go into a trenching routine followed by the drilling of the vertical holes. Fluidic control devices of the type investigated at the Naval Ship Engineering Center, Philadelphia (Wexler, 1969), should be particularly useful in developing the numerical controls seen to be desirable.

In summary, excavation at the extreme depths to be encountered in the DOT program probably will not allow for a man-controlled machine. Specific excavation functions can probably best be controlled by the numerical and computer techniques used with precision manufacturing machines, especially the milling machine. Optimum use of hydraulics, including fluidic control devices from the first should reduce cost and increase reliability. The technology is available for adaptation.

The results of a major analysis and preliminary design (Northrop, 1970) indicated that there might be a major technological deficiency in the present ability to accurately position a cutter in a real-world domain. Approaches and possible future work in this area are discussed in "Shallow Drilling and Excavating" of this report.

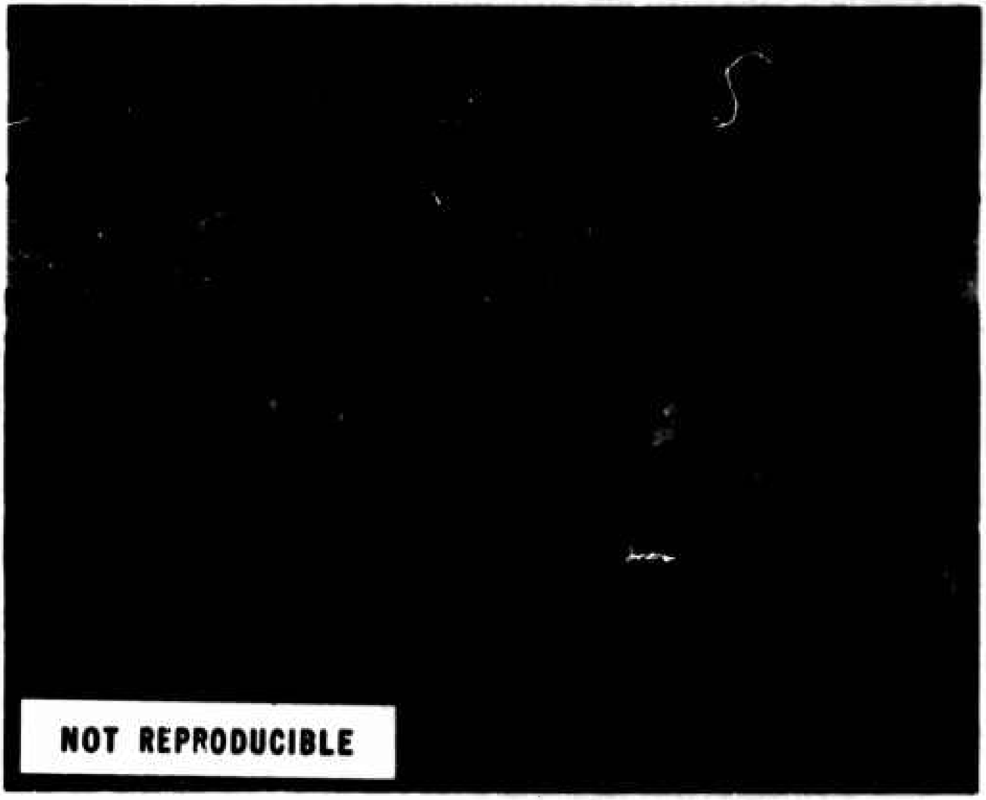


Figure 55. Soil cutter and pump undergoing preliminary testing at NCEL, working in a hole filled with water in hard, rocky soil.

CASING THROUGH SEDIMENTS

Over a major part of the deep ocean's bottom, the basement and sedimentary rocks of the earth's crust are overlain by layers of sediments to various depths. This is so because (1) currents carrying heavy media eventually deposit it in the depths, and (2) materials coming to rest on the ocean's surface such as dust, nonorganic debris from marine life, and volcanic ash would fall vertically through the water, in the absence of strong currents. Even with strong currents particulate matter would be rather uniformly distributed, except near shore. Such heavy materials are represented by mud slides and sand falls, especially near shore. In the Pacific, recent theories of floor spreading are well correlated with known rates of sedimentation. The deep western Pacific, the point of submergence of the crust below Asia, has very heavy layers of sediment; this agrees well with the spreading rate. The eastern Pacific, or "new floor" has a relatively thin layer. Only on steep slopes or summits of seamounts can exposed rock be expected with any certainty.

Useful locations for subbottom installations of the types discussed in the next section might not be where the rock is exposed. Typically, it might be necessary to penetrate a significant layer of silt, clay, or ooze. To drill into the rock with a large drilling machine, it will be necessary to sink a large-diameter casing to rock, make a minor penetration and grout or otherwise set the lower end of the casing in the rock. The enclosed sediment could then be rather readily removed by pumping or jetting, or a combination, depending upon the consistency. In any case, the sediment removal appears to be the only part of the operation which can be done with certainty by existing, proved techniques.

The anchored casing would be useful for subsequent operations, as it could form a guide for the large-diameter boring machine of the type shown schematically in Figure 56. This would solve a difficult problem of vertical stability and obtaining initial entry with the large machine, which must be guided until it makes penetration.

The presence of this large tube will not simplify entry to the underground workspace, however, because it must remain as part of the completed installation. But, if techniques for securing a positive seal at its lower end can be developed, it would be comparatively simple to make the final closure at the top of the tube (point A, Figure 57). This could readily be entered through a suitable hatch system from either a small submersible or a personnel transfer capsule (PTC). It would be possible in principle to enter from a suitable personnel transfer capsule if the pressure closure were made at the bottom of the tube, but this method does not appear attractive from a safety and utility standpoint under present concepts for control. Considerable study will be required before such an operation can be conducted with confidence. The presence of the tube would also complicate the process of subbottom excavation and spoil removal. These problems would be mitigated by drilling a very deep hole which could be used for storage of spoil from the lateral excavations (Figure 58b).

On a small scale, the initial penetration of the tube into the rock would present no problems—there are many commercial cylindrical coring augers which can readily trepan to considerable depths with modest power requirements (Figure 59). Extending the technique to very large cylinders, it is reasonable to consider the details of fitting cutters to the lower edge of a cylinder perhaps 30 feet in inside diameter for trepanning several feet into the rock. The large area in shear and the high apparent viscosity (Reiner, 1954) which might be expected would make rotation of the entire cylinder difficult, although ways could be visualized to reduce the drag. Pumping seawater through orifices near the bottom to the outside, forming a film of water along the outside would be an example. This particular configuration probably would provide the necessary vertical stability if the sediment were fairly viscous; the water would provide the lubricant and the whole assembly would perform like a journal bearing.

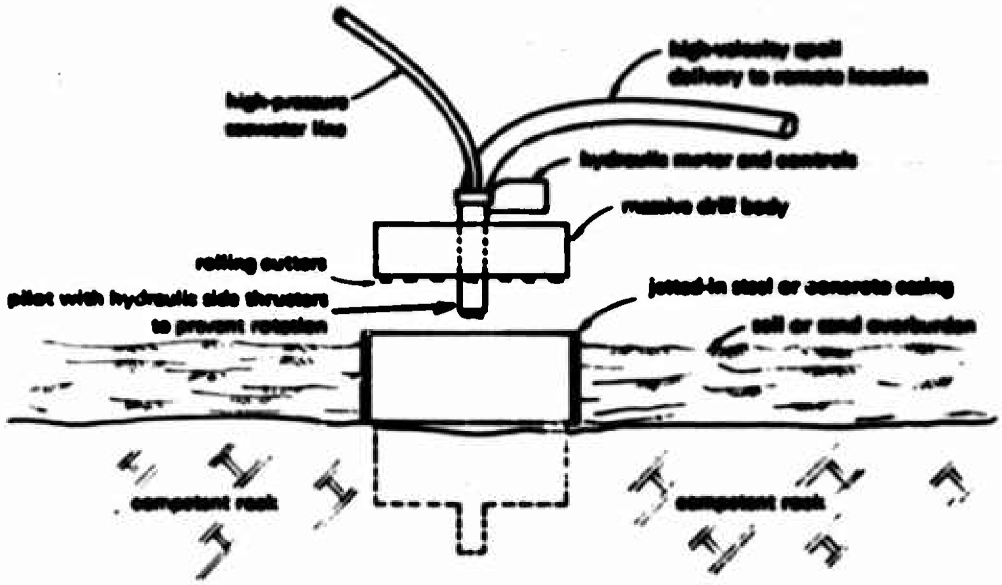


Figure 56. Seawater-hydraulic-powered large-hole rock drill for making initial penetration into seafloor.

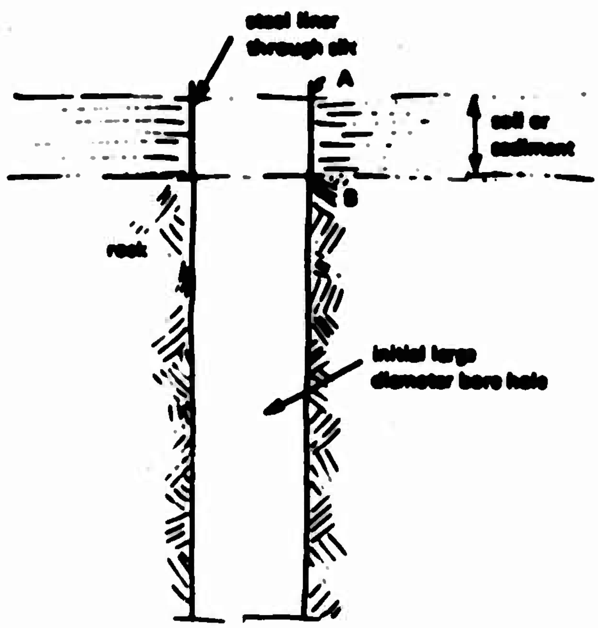


Figure 57. Method of casing through silt overburden.

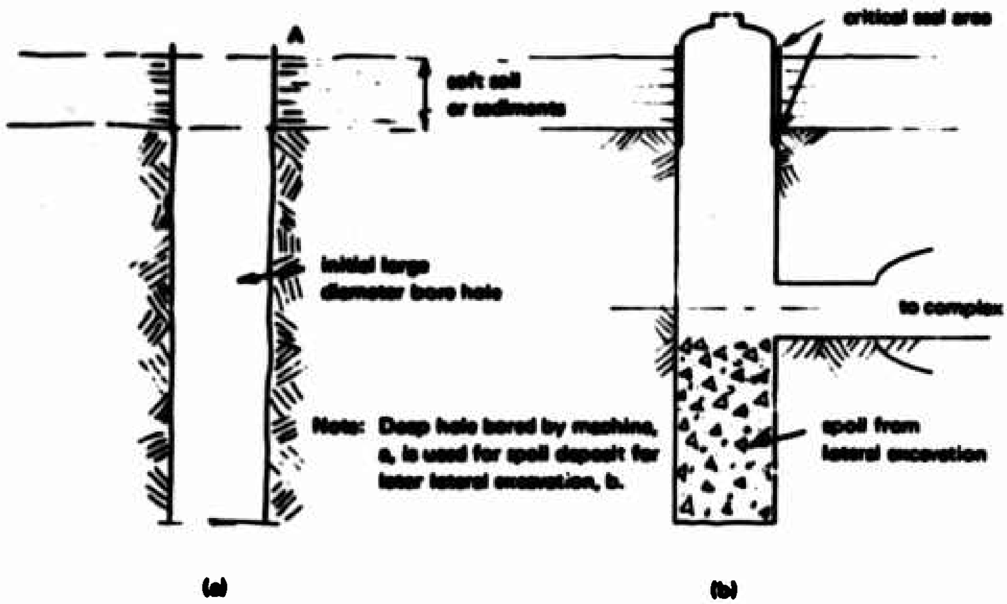


Figure 58. Method for spoil removal from living complex.

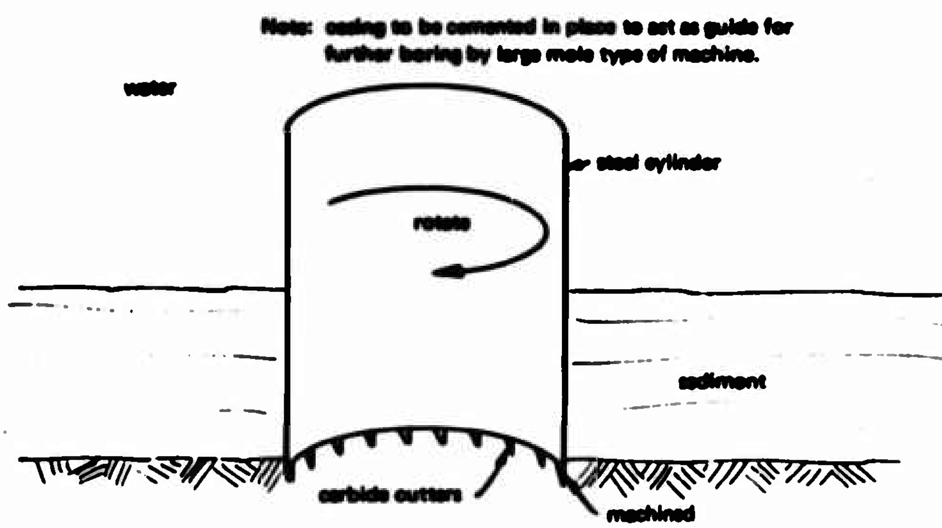


Figure 59. Method for using steel casing with carbide cutters for cutting through sediments to bedrock.

A possible alternative which would not require rotation of the long cylinder is shown in Figure 60. Here, a large steel tube would be placed by gravity or some method of forcing it through the sediment until it contacted and rested on the rock interface. A slightly smaller hole would then be trepanned in with a special cutter, which might fit the large boring machine eventually used to bore into the rock. A special internal drag cutter or grinder would precisely form the grooves, etc., as necessary for grouting in the closure head.

Summary

For placing large hole borers in the basement rock of the sea bottom, it may frequently be necessary to penetrate an overburden of soft or broken rock or unconsolidated sediment, using a steel cylinder grouted to the basement rock. This cylinder might serve to pilot the large hole-boring mechanism. This cylinder will probably incorporate a final closure to facilitate approach and entry from a small submersible or PTC. It might also serve to carry special equipment for pumping, rock discharge, etc.

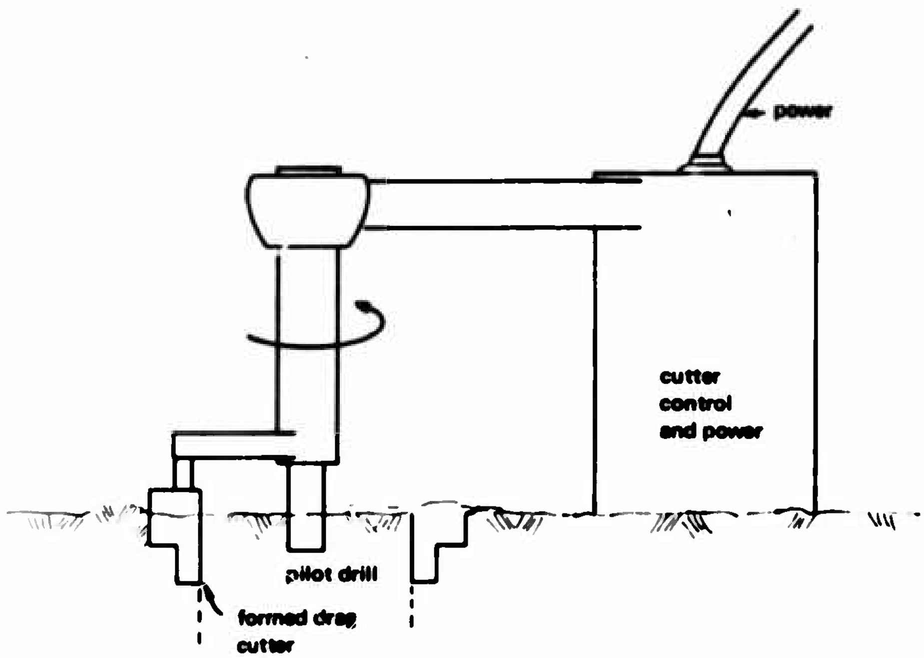


Figure 60. Concept of a specialized machine to produce precise smooth groove for setting a steel liner in bedrock.

Future Plans

The first effort in designing the cylindrical enclosure for sediment penetration appears to be an investigation of the potentially severe structural problems which will occur upon dewatering and externally loading the cylinder because of dimensional change at the steel–rock interface. The nature of these structural problems is described in the final section of this report.

LARGE HOLE PENETRATION OF COMPETENT ROCK

The central problem of rapid tunneling in rock today is the development of rock fragmentation techniques which will allow the use of semiautomated equipment of the type shown (Figure 56) in very hard, unfaulted rocks such as granite and basalt, to name two of the more difficult. This initial brief study of the problems has been greatly facilitated by three recent comprehensive studies (National Research Council, 1968; and Nasiatka, 1968). A concise compilation of cost data (Hill, 1968) is also very timely, as cost is a major factor.

Two particularly important points are quoted from the National Academy of Science Panel Reports:

> [I] t is clear that material improvement in cost and productivity in tunneling must focus on the rock disintegration process. Generally rock which is weaker than the usual concrete offers no serious problems for any of several well-known methods of disintegration.

The probable hardness* and compressive strength of rocks in the ocean is very high. This is the basis for the proposed type of one-atmosphere construction which depends on the strength of the rock to withstand the hydrostatic pressure surcharge upon dewatering. If this assumption of the ubiquity of hard rock is correct, major improvements in rock disintegration methods may be needed before subbottom drilling and excavation can be accomplished in any but selected, favorable rock formations. On the other hand, a recent survey article (van Andel, 1968) indicates that fairly soft rock might be expected near the water–bottom interface in most parts of the world. At this stage of investigation, it is necessary to consider all possible contingencies of rock hardness, including the most difficult to penetrate.

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* It is generally agreed that hardness and/or compressive strength of rock may not be the real criteria for difficulty of fragmentation. The usual small diameter core tool produces a cylindrical specimen which is typically tested in axial compression. The tunneling and mining industries have related excavation rate to such test results as a convenience, but they are searching for a better index, which is badly needed as a basis for research.

In establishing a subbottom facility in competent rock, there appear to be two distinct types of excavation, probably with separate solutions. In Figure 58a, a large-diameter vertical hole is shown in the bottom rock. Entry is made through the overlying soft material by casing and pumping as discussed earlier in "Casing Through Sediments." The vertical hole would be bored by a specialized mole initially guided by the steel casing through silt. The mole would receive its power from the surface and would make initial penetration into the rock under its own weight. Once into the rock, it could react hydraulically against the rock walls to augment the weight in downward thrust to obtain maximum drilling rate and optimum tool life. The machine parts would be exposed to full ocean pressure. As seen now in terms of conventional tunneling, the most difficult aspect of this operation is replacing worn cutters. The best (and probably most expensive) cutters available would be used to avoid retrieval of the mole for cutter replacement. If practicable, boring of the desired vertical hole without cutter replacement should be planned, even if this should lead to very high cost cutters being used. The spoil would be pumped to the surrounding ocean bed.

The second mode of operation to be used in the lateral excavation from the vertical shaft (Figure 58b) might be done with a smaller specialized drilling machine (mole), or specialized fragmenting and mucking techniques capable of excavating large noncircular caverns of perhaps very complicated plan. In above-sea-level operations where air is plentiful and integrity of the surrounding rock is of less importance, this type of excavation is most frequently and inexpensively done by drilling and blasting. An interisland tunnel between the main islands of Japan is being built by drilling and blasting, but with damaging effects. Drilling contractors from this operation attended a major international symposium on excavation in hopes of hearing of an excavation method which would cure their troubles (National Research Council, 1968, verbal comments at meeting). Blasting is a drastic process, only partially controllable, that causes considerable overexcavation and breaking of the surrounding rock, leading to excessive entry of water through the cracks. To seal these, all the overbreak must be replaced with a concrete or other waterproof liner. In the deep ocean, an additional problem, hydrostatic head on the excavation, will arise once the entry shaft (Figure 58a) has been sealed (Figure 58b) and the cavity dewatered. At great depths (6,000 to 12,000 feet), the requirements for continuous rock integrity will be so great that drilling and blasting, even if technically practical, will not be permissible. Rather, a more precise and gentle method of local disintegration of the rock will be needed. Many methods have been proposed (Maurer, 1968), but not all have been investigated. These methods and some variations are discussed later in this chapter.

Aside from the objections listed above, blasting probably will not be feasible in the subbottom installation excavation because toxic fumes are produced, to say nothing of excessive dust. This is usually counteracted by ventilating with large amounts of fresh air, which will not be available in the subbottom excavation site. If drilling and blasting prove to be the only means feasible, development of fume-removal techniques and systems will have to precede construction of the first installation.

Since almost any method of excavation developed will undoubtedly produce some fine particulate matter, environmental control (that is, control over the quality of air in the excavation) may be required and may prove critical in the selection of a disintegration method. While environmental control may prove difficult, it should be accomplished with known techniques or those under development. Environmental control is a major aspect of the research recommended by the NAS study (Hartman, Jacobs, and Williamson, 1968).

In conclusion, a note on spoil removal. It is planned to remove spoil from the vertical shaft by pumping a slurry of fragments and seawater. Various methods have been suggested for excavation in a normal atmosphere and ejecting the spoil through water-tight pass-throughs (Figure 61). Unless a second penetration from the sea bottom is made and connected via lateral passageways, it will be necessary to incorporate the spoil removal lock system in the same pressure head as is used for ingress—egress from a submersible.

Improvement in Methods of Rock Fragmentation

From the earlier discussions in this chapter and under "Spoil Removal," it is clear that while it may be practicable to use conventional large-diameter boring techniques for drilling into the hard rock bottom of the ocean, it will be costly. This is so because available machines are very heavy and complex; generally the spoil is removed in large pieces which do not lend themselves to slurry pumping. Thrust forces against the work face are very high, as are the torque requirements for rotating the cutting assembly against the work face. The machines are generally long in the dimension of their rotational axis, and guidance is difficult until the penetration of at least one machine's length is made.

Rock fragmentation (comminution) techniques which will perform in a less massive machine would presumably eliminate many of the expensive development problems in adapting the established borers to the deep-ocean floor.

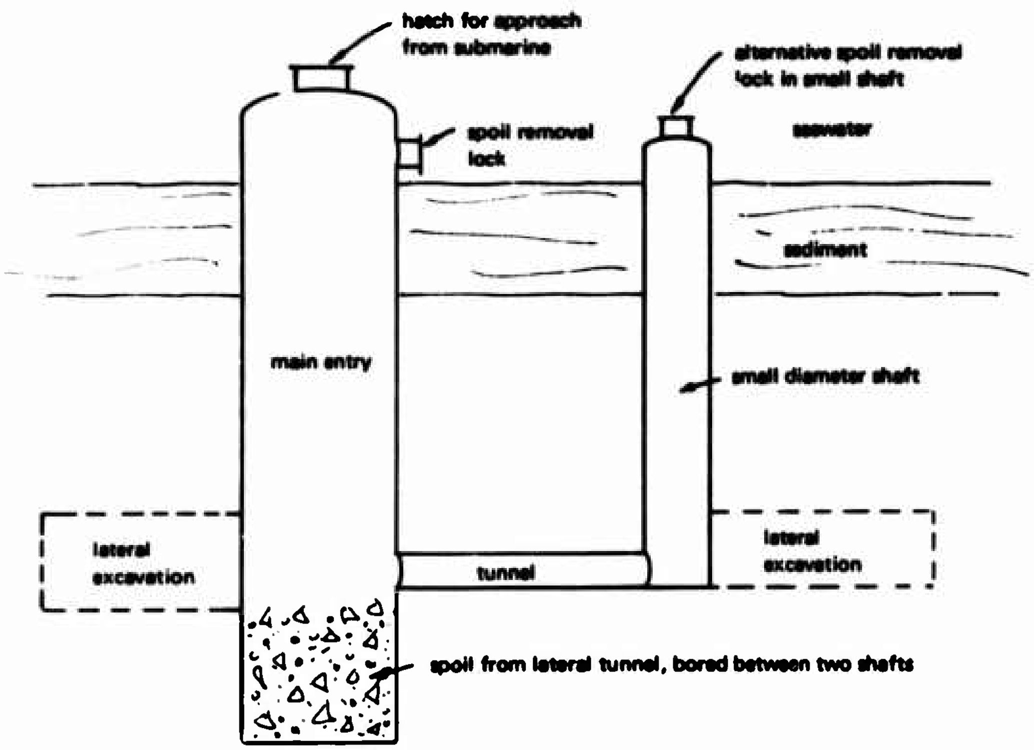


Figure 61. Spoil removal schemes.

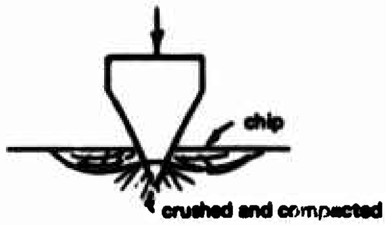
Some notes on the important physical characteristics and weaknesses of rocks, some observations on how mechanical penetrators probably function, novel drilling methods which have been considered, and possible additional approaches which appear to have merit are discussed below.

Walsh (1965) gave a thumbnail sketch of the physical nature of hard rock. Paraphrasing his remarks may provide a worthwhile understanding of the nature of the material. Under photomicrographic examination, rock appears similar to many metals. It has grains and grain boundaries just as do the metals, and little difference is seen upon superficial examination. However, upon close examination, differences are seen. A network of fine cracks on the order of 1 mm long by 0.001-0.0001 mm wide can be seen within the grains, along the grain boundaries, and across the grains and boundaries. These cracks are probably caused by extreme anisotropy of the individual grains. The rock is solidified deep in the earth at very high pressure and upon release of this confining pressure when the rock is brought to the surface and to atmospheric pressure, stresses high enough to produce the fine crack network are generated. The crack network interconnects to such a degree that under sufficient pressure, water can be forced through a slab of granite 6 inches thick. While extremely strong in compression, rock is therefore relatively weak in tension, and most of the rock failure methods in use or suggested are designed to take advantage of this weakness—actual failure occurs in tension although the method may apply pressure at a point or shear over an area.

Most of the rock destruction methods in use and historically important use indentors of one form or another, but stress patterns and true causes of failure are not well known. An excellent discussion of rock indentation is given in Cheatham (1968). Figure 62 (Hartman, 1959) illustrates the method by which spalling over a large area can be induced by a sharp indentor. Figure 63a shows a point load on an infinite half space. When second-order effects are considered, it is found that the line A-A has increased in length, after indentation and the material is therefore under tension. Two-dimensional elasticity theory shows that in the linear solution the surface well away from the indentor is stress free. Figure 63b is a sketch of the Hertz solution for a two-dimensional mechanical indentor. Clearly, some similar line is under tension here also. Along these radial lines of tension some maximum value exists, as does a random distribution of microscopic cracks. If Figures 63a and 63b are thought of as viewed from above down onto the halfspace and axially along the indentor, the lines of constant surface tension will be concentric circles. Thus, along some jagged circle near the maximum tension region and depending upon the particular pattern of Griffith cracks, a gross circle should appear and penetrate into the surface (Figure 63c), leaving an unsupported column opposing the loading force. Tension is produced in this column upon loading according to Poisson's expansion theory.

Whether or not this brief discussion accurately describes local failure induced by indentors, it seems clear that most successful techniques for drilling and crushing hard rocks take advantage of the material's weakness in tension by these or similar mechanisms. Cutters with teeth which roll over the surface of attack, whether they be steel, diamond, carbides, or whatever should similarly create high stresses. The rapid development of these cutters has depended upon a combination of improvement in roller materials and in methods of creating the very high forces normal to the work face necessary to achieve rapid cutting. Within the last year, improved cutters have successfully worked very strong rock which a few years ago would have been considered impossible to cut.

The following section is a discussion of proposed and sometimes tried methods for causing local failure of rock by impact or other energy transfer methods. A later section discusses the use of vibration in enhancing fragmentation without the large forces characteristic of current boring machines.



(Reprinted from an article by H. L. Hartman, "Basic Studies of Percussion Drilling," Mining Engineering, Vol. 11, no. 1, January 1959, p. 68-75.)

Figure 62. Chip formation by a percussive drill bit (Hartman, 1959).

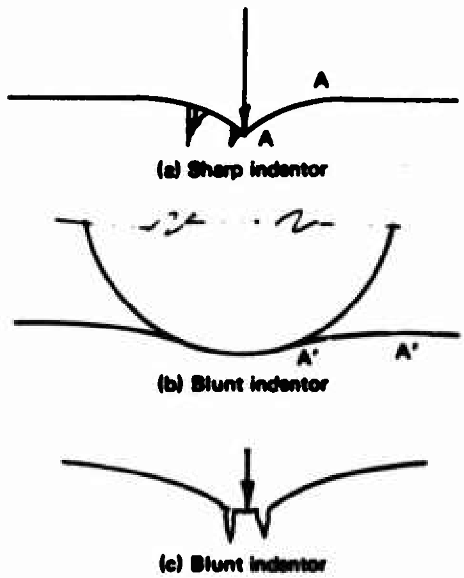


Figure 63. Proposed method of rock failure under sharp and blunt indentors.

Novel Drilling Techniques

Known approaches to nonconventional drilling and fragmentation of rock have been recently summarized by Maurer (1968). This section discusses those methods which appear to have merit for deep-ocean drilling.

Nonconventional approaches can be grouped into four categories, according to the method of inducing local stresses in a rock mass, or otherwise destroying its competent structure:

1. Mechanically induced stress
2. Thermally induced stresses
3. Fusion and evaporation
4. Chemical disintegration

Because of the presence of high-pressure seawater at the drilling site, items 2, 3, and 4 do not appear to have merit for making the initial penetration into the ocean bottom. Some might be considered for lateral excavation in a sealed-off, one-atmosphere environment but would probably be undesirable because of their potentially toxic effect on the cavern's atmosphere. Spalling by an electrically heated plasma torch might be an exception, since it does not involve combustion but could use electrical energy. The important approaches to mechanically inducing stresses are discussed below.

High-Pressure Water Jets or Erosion Drills. With sufficiently high velocities, jets of water are able to spall the hardest rocks without the use of abrasives. Ostrovskii (1962) and Zelenin et al. (1958) report on a four-nozzle drill with 1-mm nozzles delivering water at a pressure of 1,000 atmospheres and drilled granite at 15 cm/min. Maurer (1968) cites many experiments in which rock has been effectively cut by water jets. At the present state of technological development in the United States (Cooley, 1968), practical machines have been limited to spalling of relatively soft sandstones and breaking harder rock such as limestone. Present water cannon designs probably are not the answer, but free jets working on a shaped-charge principle may well be.

Down-Hole Turbine Drills. Diamond-faced cutter wheels are rotated at 5,000 to 10,000 rpm by a turbine on the end of a drill pipe, with the drill pipe itself rotating at 30 to 75 rpm. The turbines receive hydraulic power and are about 10 to 20% efficient. Drilling rates are comparable to rotary drills but always lower. Diamond cutters require twice as much energy as drag cutters, and present turbines are limited in power; better and more powerful turbines will be required to make this concept useful. Some commercial models are available.

Pellet Drills. Recirculating steel pellets are fixed against rock to fracture it. A drilling fluid is pumped down a drill pipe through a nozzle which by aspiration draws in the pellets at the bottom of the hole and fires them at the rock at a velocity of about 23 m/sec. A secondary nozzle accelerates the rock particles. Some 80% of the cuttings in the fluid are recirculated while the remainder are carried to the surface. The difference in densities tends to keep the steel pellets at the hole bottom while the lighter cuttings are carried off. Only about 4% of the power is delivered to pellets, limiting the effectiveness. Water has been found to be the optimal fluid. The effectiveness of some thirty-five different pellets was investigated before the study was discontinued. In Maurer's (1968) opinion, a major change in basic concept will be required to achieve acceptable efficiencies.

Continuous Penetrators. Continuous penetrators are hard-pointed metal pilings that are forced through the rock. High forces are developed by the combined weights of the drill collars, impact loads, and wall anchors; a hydraulic cylinder can be used to give additional force. The rock for some distance around the penetrator must be crushed to permit flow around the penetrator, with the diameter of the crushed region dependent upon the porosity of the rock. Maurer (1968) cites a case in which rock of 5% porosity was crushed to a diameter of 20 cm with a penetrator of 5 cm diameter. Because of the very high forces required for hard rock, this method is only used in weak rocks or unconsolidated materials.

Implosion Drills. Implosion drills produce rock failure from implosion of sealed capsules at the hole bottom. They are pumped in a slurry to the hole bottom. The collapsing cavities create high pressure pulses in the fluid, for example, 32,600 kg/sq cm when a 50-mm-radius cavity collapses to 5 mm in a 2,000-meter deep hole filled with water. Energy is dissipated in the fluid and only a small amount is transmitted to rock. To achieve the equivalent of 30 to 50 hp requires about 13,000 10-cm spheres per hour at a depth of 2,000 meters. Capsules are probably expensive, and not all stone is shattered effectively by this method.

Spark Drills. Spark drills use an underwater spark to produce shock waves. Energy stored in condensers flows through a small conducting zone, creating a high-temperature plasma which exerts pressure of 10^4 to 10^5 atmospheres in the water confining the spark. Sparks lasting from 5 to 50 μsec produce instantaneous power release at a rate of a million horsepower. Energy from a 4 μf capacitor charged to 70 kv is 9,800 joules; firing 10 shots per sec would be equivalent to 133 hp. Sparks appear to require about twice the energy of conventional drills for the effects produced, but they have a high potential because they can be operated at high frequency. By comparison, a large rotary drill can deliver from 20 to 50 hp.

Maurer (1968) has proposed a spark percussion drill in which sparks confined behind a piston drive a conventional bit. No data are available, but the Soviets are believed to have tested this approach.

Electrohydraulic Crushers. Electrohydraulic crushers use a variation of the spark drilling technique. Epshteyn, Arsh, and Vitort (1960) used sparks in a tank, with 0.19 μf at 40 kv discharging 5 times per second to reduce shale and chert from 7 cm to 5 mm in diameter. Bergstrom (1961) used a 0.05 to 0.5 μf with up to 80 kv to crush limestone to 1 mm. Maroudas and Taylor (1964) used 0.005 μf at 30 kv to crush glass spheres to 0.3 mm.

Mechanically Induced Stresses. Explosive drills pump 3 to 12 explosive capsules per minute. The capsules explode on impact with the rock. The Soviets have pumped twelve 50-gram capsules per minute, releasing some 66 hp. The capsules must be spaced so that one does not detonate while the next is in the nozzle. Drill rate does not appear to depend on rock strength, but the system cannot drill soft materials which cushion the blow and are difficult to remove from the hole. The system as tried was limited by spoil removal rate, but in hard rock penetration was comparable to that of conventional drilling methods.

The Russians also have tried a drill using liquid explosives with cyclical mixing of liquids by differential pressures. While the potential power is greater than for solid explosives, tests of the drill were unsuccessful. Flushing fluids diluted the explosive liquids, and explosives accumulated and destroyed the drill.

Concepts for Rock Fragmentation by High-Frequency Vibration

The possibilities of avoiding use of a high static force or low-frequency dynamic force and the attendant heavy machines are especially attractive for deep-ocean applications because of the difficulties in reacting large forces on unstable ocean bottoms and in lowering heavy machinery from the surface. An ideal although probably impractical drilling machine would be light in weight, would react against the ocean water, and would have cutters capable of effectively destroying competent rock without a high force normal to the work face. An additional desirable if not required feature in a large drilling machine for subbottom rock drilling would be the lack of a cutter which requires replacement or sharpening. A rock fragmenting system which would, for example, destroy the surface by the application of high-frequency vibration or a series of high-velocity water jets illustrates the ideal. Neither rotational torque nor penetration force would be large—the system would probably also be small in dimension normal to the rock face, allowing easier access and more space for particle removal, pumps, etc. A simplified version of such a machine is shown schematically in Figure 56. The same or perhaps greater benefits would accrue from use of a similar machine in the subbottom lateral excavation (Figure 61) because of the difficulty of assembling and manipulating the typical long boring machine in close quarters.

A quotation from page 54 of the National Research Council report (1968) corroborates views presented above:

> Present designs involve massive structures with accompanying problems of lack of flexibility, high capital cost, difficult maintenance, etc. One method of reducing this could be to introduce percussive energy through high frequency, low energy blows. Successful application of such new techniques would lengthen cutter life and lessen the thrust, currently needed.

Identical forces applied statically and dynamically result in stresses that differ for elastic materials by a factor of two, with the higher values resulting from high dynamic load rates. Thus a 100% increase in efficiency might be anticipated in a mechanism which could capitalize on this difference in resulting stresses. It would be important that the load be applied significantly faster than the propagating mechanism could remove the energy within the rock. The velocity of the indentor must exceed some critical value of velocity for each rock. Determination of these values awaits suitable experiments with various rock types.

It is a generally known fact that the most massive of structures is potentially subject to destruction if it can be excited at or near its natural frequency of vibration and if its inherent damping is small. The spectacular failure of the main span of the Tacoma Narrows Bridge in the State of Washington in the early 1940s when excited by wind gusts is a case in point. At the other end of the size scale one might hope to destroy rock with high-frequency excitation at the natural frequency of the very small rock particles as isolated, for instance, by the Griffiths cracks. A simpler system might be developed which would use broad-band random vibration with an upper frequency cutoff such that all rock would be disintegrated to very fine particles. Among other methods, a liquid bath might transmit this vibrational energy to the rocks. Experiments are planned to determine the degree of damping in rock vibrating in its first mode. Experiments would be run to determine if rocks can be sufficiently excited in a liquid bath. Finally, the effect of the broad-band random excitation would be studied.

While the problems to be overcome appear formidable, the possible benefits to be gained are large compared with the modest experimental and theoretical program necessary to establish the necessary foundation of equipment development.

Current Activity in Research and Development

Major efforts are in progress to develop at least two systems which do not depend upon a cutter to disintegrate strong rock and thus avoid the problem of cutter replacement. Recent work at Westinghouse Research and Development Center, Pittsburgh, Pennsylvania (Schumacher, 1968), has made electron-beam heating of rock practicable in a one-atmosphere situation, with the further ability to work under a small (few inches) water head. Since the beam of electrons is rapidly scattered and absorbed except in a vacuum, the device must be close to the rock. The vacuum is maintained by a series of chambers, each of increasing pressure as the electrons approach the outlet. An overpressure of air in the final stage prevents the ingestion of gas and dust into the vacuum system and allows submergence in water. The method is not currently applicable to working under high pressures in the ocean, but may prove suitable for the subbottom tunneling of lateral chambers. The only requirement is for electric power, with the possible exception of a requirement for selective removal of noxious gases from the closed atmosphere if they are released upon heating the rock. The present state of development is a laboratory model of a cutting gun capable of melting or splitting its way through 4 to 6 inches of rock by local heating from an electron gun. The decelerating electrons give off X-rays, but the process is amenable to remote application so shielding requirements would be minimal. The necessary development will be in manipulating a gun of optimum design for cutting into competent rock, developing methods of quenching to optimize spalling, and a machine to hold and move the gun. A suitable model of a gun is believed to have been designed by Westinghouse.

Fully developed, the electron beam cutter for rock is believed to be one of two methods suitable for use in the subbottom excavation. The other method, which appears feasible in both the one-atmosphere situation of the subbottom cavity and the full pressure of the ocean, is the high-velocity water jet (Figure 64) under development by the Exotech Corporation of Rockville, Maryland, and under research by others (Maurer and Heilhecker, 1969). The later work proves the feasibility of erroding very hard rock if sufficiently high velocity (high water-nozzle pressure, usually) can be achieved. For deep-ocean rock excavation, the method appears to be especially advantageous in that the power is conveniently and probably preferentially transmitted as high-pressure hydraulic power in a hose. It can then be locally intensified by use of variable-area piston pumps (one large piston at the lower pressure directly connected with a small piston on the same reciprocating rod) with pressure intensification at approximately the ratio of the piston areas.

Two important methods of jet formation are recognized. First, the straight jet with a velocity $V = (2gh)^{1/2}$, a well known hydraulic relationship. This type of jet has been effective in drilling rock with pressure heads of 8,000 to 16,000 psi (Maurer and Heilhecker, 1969). Presumably even more effective are single-shot machines using a formed capsule of gelatin. In jets of this type, a conical impactor reacts kinetically to accelerate the shaped gelatin in what might be called a "shaped jet," which is free standing and not subject to the usual limitations of hydraulics, including wall friction. Stagnation pressures are reportedly achievable of about a million pounds per square inch. Losses in the velocity of the jet can be established by equating the momentum of the impacting conical ram and the initially stationary cylinder of gelatin, which acts as a liquid at high flow rates. In its present state of development in the United States, the system is limited by the single-shot aspect and the requirement for a shaped annular cylinder of gelatin which must be replaced after each shot. A recent disclosure (Beck, 1970) of a method of using water and providing for rapid replenishment of the charge (to make the device rapidly repeating) needs demonstration, but is entirely practicable theoretically (Figure 65). Incorporated into a system such as that shown schematically in Figure 64, it should be possible to work in the vertical position in the deep ocean, with a charge of air at the local sea pressure in the pressure head. To achieve the centrifugal configuration of the working charge of water, it is clearly necessary to have two liquids of different densities, the lighter of which could be an immiscible liquid or preferably a low-molecular-weight gas such as helium or hydrogen to minimize frictional losses. Air should be entirely satisfactory for most conditions and pressures, although there may be some loss in efficiency strictly on the basis of the high viscosity and density of air at high pressures. Whether the potential advantages of the lighter gases outweigh the disadvantages of special handling, supply, and cost remains to be proved by trade-off studies and tests.

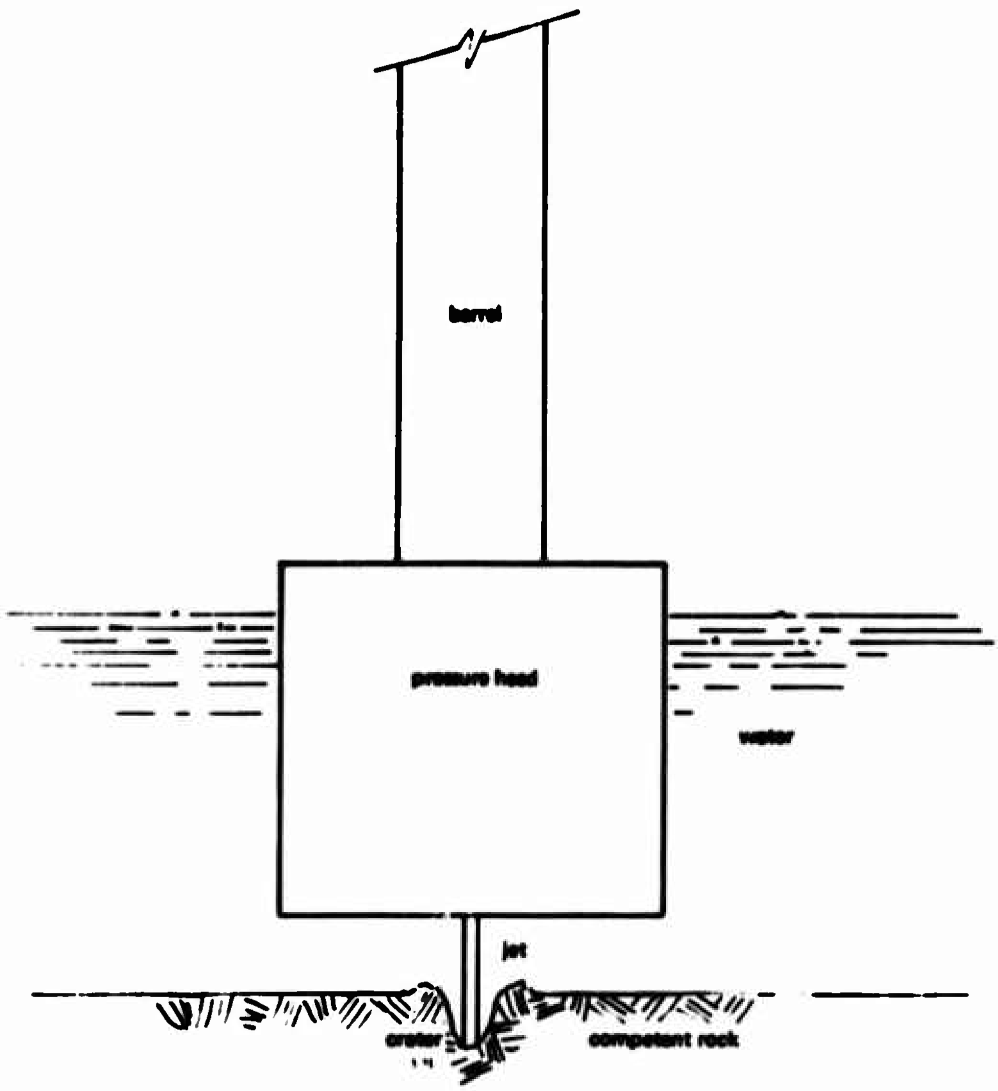
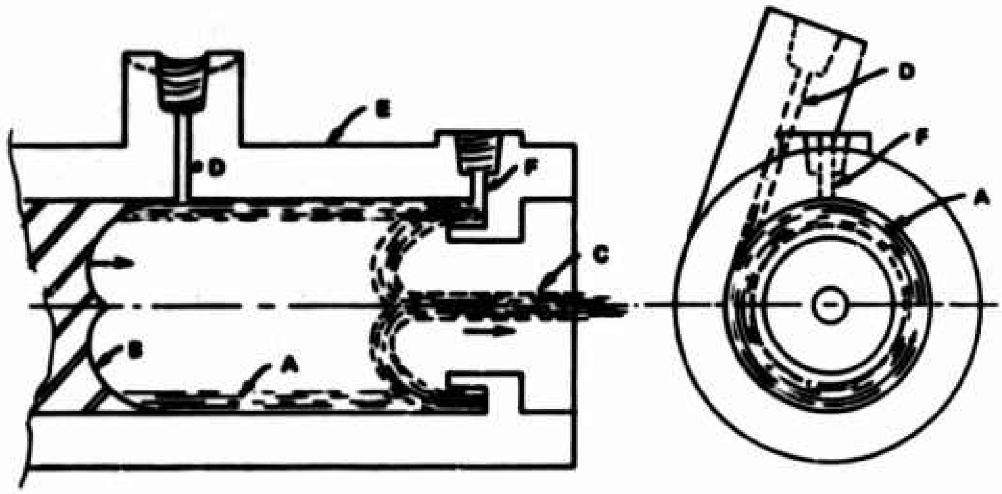


Figure 64. Test of high-velocity water jet for penetrating hard rock (Cooley and Clipp, 1969).



Stable annulus of water, A, is repeatedly formed and then is repeatedly and rapidly impacted with high velocity steel impactor, B. This forms a small, extremely high velocity water jet, C, which can be used for breaking brittle materials such as rock. In use, water is introduced through a tangential hole, D, into an annular space in a cylinder, E. Surplus water is collected at suction hole, F, to avoid possible interference of any excess water with the working jet, C.

Figure 65. Method for repeatedly forming a stable annulus of water.

An example of local destruction of a single shot in Barre granite is shown in Figure 66. About 7 in.^{3} of rock was removed with a jet of 750,000-psi stagnation pressure.

Either of these special rock destruction techniques, the electron beam or high-velocity water jet, promises to reduce the rotation, torque, thrust, and atmosphere contamination common to large boring machines employing cutter bits. However, the processes by which these are applied to a solid rock face in a controlled manner have not been worked out; these problems are to be attacked shortly. Failing successful development of suitable new control methods and excavation technqiues, there is at least one major improvement in rock bit application which might improve boring efficiency, although probably always with relatively rapid bit dulling and replacement. A series of patents (Bouyoucos and Hunt, 1958, 1961, and Bouyoucos, 1964, 1965a, 1965b) of hydroacoustic oscillators provides a method for rapidly and forcibly oscillating tool-steel or carbide cutters in drilling rock. The action is similar to that achieved with air drills but is believed to be much more effective on an energy use basis. More important, it can be operated with pressurized seawater (in a proposed design), and the discharging seawater can be used to flush chips from the work area. General Dynamics Corporation controls Bouyoucos's patents and has prepared a design of an oscillator

(Figure 67) which might be of a size and type suitable for multiple mounting on a large rotating disc for large-diameter hole boring. This model does not have direct impacting of the oscillator with the work tool anvil as does an earlier drill model; it is simplified in sealing, construction, and use because of the self-contained aspects of its construction. Its efficacy remains to be proved in deep-ocean applications, but it almost certainly will prove advantageous in loosening soft rock, hard soil, etc., and reducing cutter forces. A prime feature of this type of oscillator is the very high energy input—50 hp in the model shown; the small size of the chips produced will facilitate flushing from the work face.

Summary

Of the nonconventional methods of destroying hard rock, the use of very-high-velocity water jets for spalling, and of electron beam cutting and spalling appear the most attractive for early development for deep ocean bottom work. The electron beam in its present state of development is not adapted to a high-pressure water environment, except in vertical drilling, but the water jet does appear to be wholly suitable. Development of supporting and movable machines capable of using these techniques advantageously is needed.

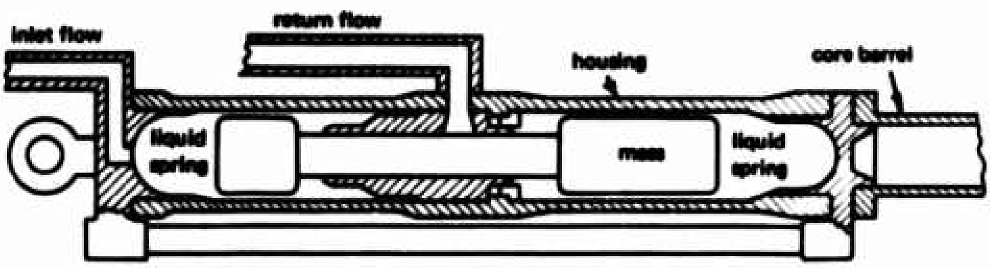
If neither of the above methods proves workable, rapid oscillating of a number of carbide bits mounted on a rotating work face probably will offer some advantage over the present cutter system.

Large hole rock penetration appears to be within the state-of-the-art so far as rock excavation is concerned, but many of the methods applicable in a one-atmosphere environment will probably not be feasible in the high-pressure environment. Systems which generate large amounts of dust or noxious fumes probably cannot be used because air will not be readily available to purge the excavation. Necessity for changing bits will make the use of conventional cutters on large moles undesirable.

Future Plans

New rapid excavation techniques in rock should be further investigated, with some support given to those that appear most useful in the high-pressure water environment or in the one-atmosphere environment of a sealed-off cavity under the ocean. Building and test of scale-model devices for demonstrating the more favorable techniques will be in order for the next two fiscal years. The high-velocity water jet, the electron-beam, and high-impact abrasive cutting in particular appear to have advanced to the point where further investment is justified.

Figure 66. Spall crater in specimen of Barre granite made with a single shot of cumulation jet under water.



General Dynamics Underwater Vibrator IFO-1AP05369. Vibratory force is 11,000 lb at 60 Hz. This is a modified commercial device and is protected by patents and patents pending.

Figure 67. Proposed high-power hydraulic oscillator for driving indentor in seafloor rock drilling and disintegration. (After drawing by General Dynamics, Rochester, New York.)

It is planned to further investigate the current research in rock comminution by novel techniques and to prepare one or two requests for proposals. If a positive response is obtained from industry, it is planned to take the first steps toward developing machines, at first on small scale to demonstrate their efficacy. Successful tests will lead to further consideration of these advanced techniques for incorporation into the complete construction systems.

LARGE HOLE SEALING AND DEWATERING OF CAVITY

To the potential occupant of an undersea manned station in subbottom rock, probably two safety aspects will be of prime interest—the integrity of the rock in which the excavation is made, and the quality of the seal at the point of entry to the ocean (A, Figure 57). The variability of natural rock makes the former always open to question, but the problems of seal leakage are approachable by modern methods of analysis, design, and testing.

Probably largely because the levels of leakage are acceptable and the pressures and temperatures are moderate, industrial practice for many years has relied on rather simple gasketing, of which that shown schematically in Figure 68 is a common example. Here, a deformable gasket material such as rubber, leather, or a semirigid synthetic material is placed in compression by a ring of bolts or other confining mechanical device. Aging, prolonged heating, oxidation, and other chemical attack usually will change the physical properties of the materials used for the purpose and, except for low-pressure applications, some leakage usually results. Conformability allows this type of gasket to be used with moderately poor surface finish, so the joints are comparatively low cost. With increasingly higher pressures and need for rapid assembly in high production, industrial gasketing has increasingly drifted toward some form of the packing recognized for its unique merits by P. W. Bridgeman (Griggs, 1954) of the Massachusetts Institute of Technology and developed in many forms for pressures in the thousands of atmospheres. This pressurized form of gasket was based on what Bridgeman termed the "principle of the unsupported area." Griggs (1954) categorically stated that *only* gaskets based on this principle will not leak if the pressure is raised sufficiently high. The underlying principle exploited is that of having a somewhat deformable or composite gasket loaded on the high-pressure side over an area greater than that on the low-pressure side (Figure 69).

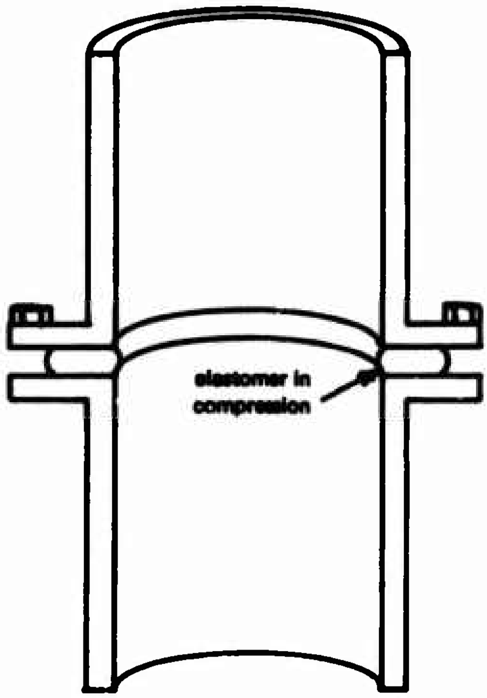
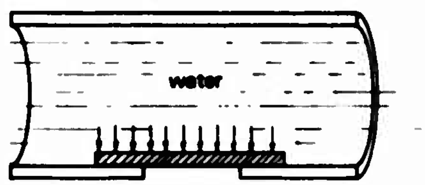


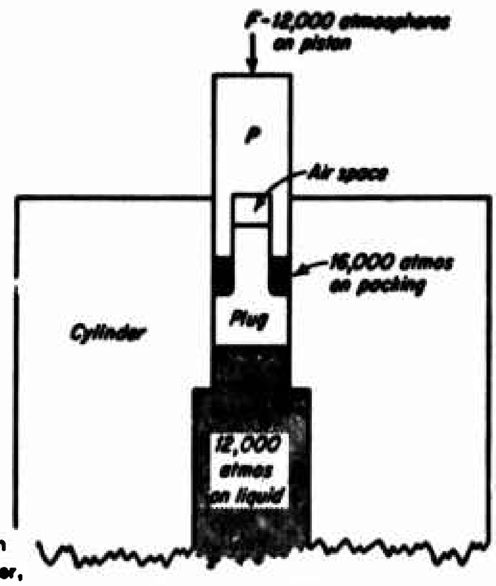
Figure 68. Conventional compression gasket.

A well-known example of the deformable gasket is the old-fashioned rubber disk overlying the drain and serving as a stopper in a bathtub (Figure 69a). A high-pressure example is shown in Figure 69b. The common noncritical application (so far as dimensions are concerned) found universally is the O-ring, usually made of a pliable elastomer but useful for higher pressures when made of harder materials. A common loose-fitting section conforming to one manufacturer's design criteria is shown in Figure 70. In 70a it is shown unpressurized as it might be at time of assembly, at one atmosphere. In 70b the same gasket is shown under pressure with extrusion into the clearance spaces exaggerated. The only requirement for successful operation is that the joint be placed under sufficient pressure to drive the gasket against the seating surfaces—at too low a pressure, leakage will occur indefinitely. In this respect, such a gasket is inferior to the earlier compressed forms, which were useful at no pressure as well as elevated pressures within limits. For static applications, O-rings are frequently placed under slight compression to insure rapid seating. They are also fairly successfully used in nonpressure applications, in which case they require heavier initial compression and are usually confined in a small groove.

A recent and timely paper by Mikesell and Brown (1968) discusses the problems at some length, although in slightly different context than the above. For very high pressures, they analyze and discuss the success of a proprietary gasket (Figures 71 and 72). Whether this configuration would be optimum for sealing large openings to the undersea base is questionable, because it may not be well adapted to repeated opening and reseating. It may, with minor modification, be useful in solving the larger problem discussed below.



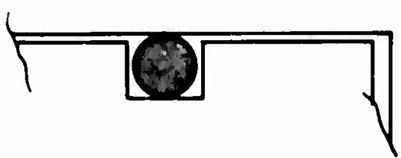
(a) flat rubber stopper



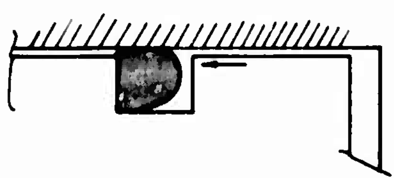
(b) stopper in high-pressure apparatus

From "High-Pressure Phenomena with Application to Geophysics," in Modern Physics for the Engineer, edited by L. N. Ridenour. McGraw-Hill, 1954. Used with permission of McGraw-Hill Book Company.

Figure 69. Examples of partially unsupported gasket concept (Griggs, 1954).



(a) Unloaded elastomeric O-ring used as a piston ring in a hydraulic cylinder. Note slight radial compression and considerable clearance i·· axial direction.



(b) With the piston working, the pressure drop is the total working pressure, and the piston seal operates with essentially zero leakage. Lubrication at the velocity interface, A, is boundary lubrication at best, even with a hydraulic fluid of recognized lubricity.

Figure 70. Action of an elastomeric O-ring used as a piston ring.

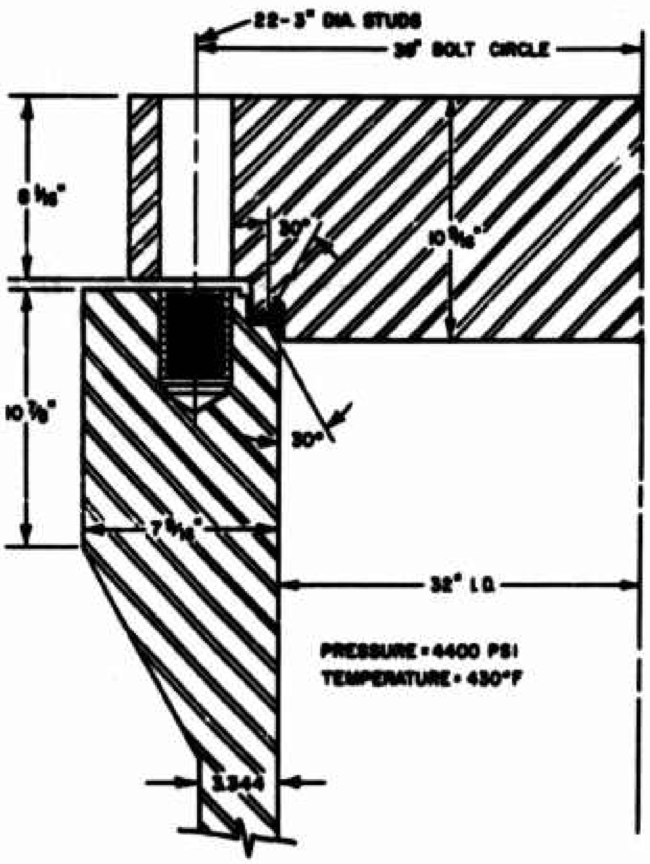


Figure 71. Proprietary gasket used on large pressure vessel closure (Mikesell and Brown, 1968).

A more difficult if no more critical problem (any significant leakage appears to be unacceptable at this writing) may arise at the point of contact between the steel insert and the bored hole in the rock (B, Figure 57). For high pressures at great ocean depths, the total design and placement procedures could be very difficult and will require the best of the available design techniques. The total joint construction as shown is not intended to illustrate correct methods, but the potential problems. A very deep steel pressure closure (approaching hemispherical) would be an optimum shape for strength, but upon seating under pressure would be reduced in diameter and break any previously made seal, such as grout. Without a step cut or ground into the rock, the axial forces would be very high, and a very long sleeve would have to be cemented into place to take the end thrust from the ocean water. An optimum design might be such that initial deformation upon loading when the cavity is dewatered would provide a calculated preload on an elastomeric seal in a ground rock seat, both axially and laterally.

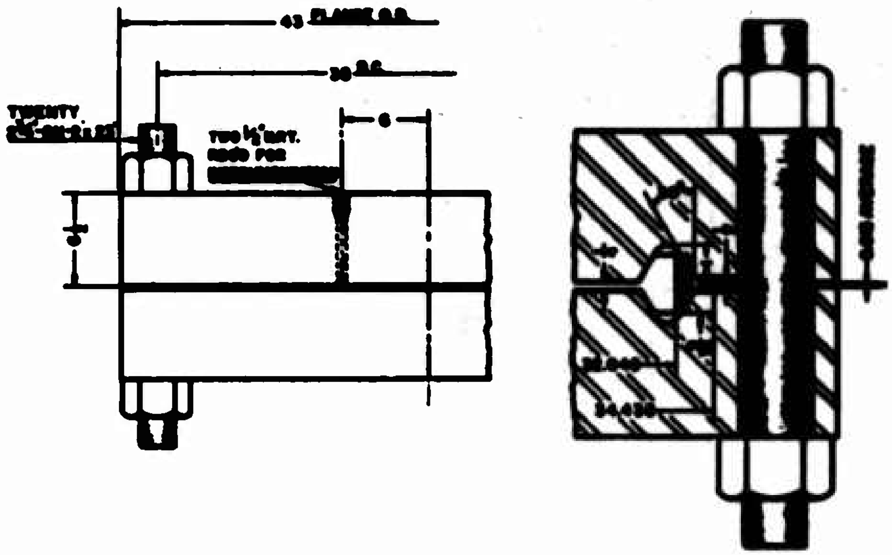


Figure 72. Experimental GRAYLOC flanged test fixture, showing details of gasket shape (Mikesell and Brown, 1968).

Dewatering of a cavity sealed as discussed above and diagrammed in Figure 57, does not appear to present any insurmountable problems but will require very careful planning. One approach might be to drop a partially insulated container of liquified air in the excavated space before closing the hatch and providing a siphon (Figure 73) so that as the liquid air boiled and displaced the water, the air would remain as a large bubble. The system would still be at ocean pressure, and a previously installed pump would be energized by power from the surface to reduce the high-pressure air to the desired one atmosphere. There would always be the danger that combustible gases from a subbottom source would provide an explosive atmosphere. Since these gases might not easily be detected or might not be released at full ocean pressure, one method might be to charge the space with liquid nitrogen initially and later provide oxygen just before the entry of personnel.

Summary

Methods for sealing and dewatering a subbottom cavity in rock appear to be within the state-of-the-art. Further trade-off studies and investigation of potentially superior systems are needed.

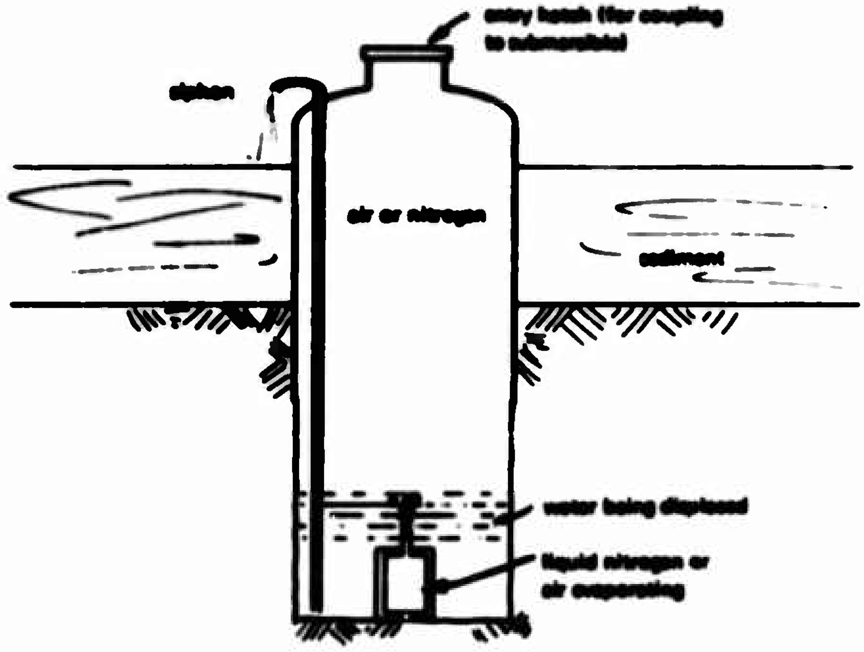


Figure 73. Method for initially dewatering entry shaft.

Future Plans

For the immediate future, possibly superior systems for sealing and dewatering subbottom cavities in rock will be investigated. These available techniques will be incorporated into a preliminary design of a complete system, which will also include casing and boring techniques.

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