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TECHNIQUES FOR UNDERWATER NUCLEAR POWER

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TECHNIQUES FOR UNDERWATER NUCLEAR POWER

Y-F015-12-04-409

Type B

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ABSTRACT

This study considers known or suggested problems in locating, handling, placing, cooling, and maintaining an unattended nuclear power plant on the floor of the deep ocean. It does not discuss the problems of reactor design and construction except as its size, shape, and effects on the environment affect the general logistic situation. The report does not state categorically that the concept is feasible with present technology, and possible avenues of approach are suggested for those areas of known deficiency.

CONTENTS

UNDERSEA NUCLEAR POWER

INTRODUCTION

The following brief study was undertaken in an attempt to reveal significant problem areas in the location, monitoring, cooling, handling, maintenance, and placement of a moderate sized nuclear reactor manufacturing power on the ocean bottom. The depth of submergence considered is between 300 and 20,000 feet, being referred to as the "deep ocean." At shallower depths, equipment can be erected and serviced by divers at the bottom. As about 95% of the world's ocean is less than 20,000 feet in depth, deeper situations can probably be easily avoided. Emphasis is placed on very deep submergence, on the tacit assumption that this represents the most difficult case. Usually this is undoubtedly true; on the other hand, many possible sites of shallower depths may be subject to unfavorable high velocity currents, higher heat sink temperatures, and particularly bad corrosion environments. These problems might make them difficult situations in comparison with the quiescent deep, once the problems of the very deep locations are solved.

The nuclear aspects of pressure vessel construction, unattended control, and reactivity life, are outside the scope of this study. The nuclear aspects have been surveyed only as necessary to establish desirable handling techniques, need for vertical stability, possible heat transfer rates, allowable convector surface temperatures, and approximate size and weight.

CHAPTER I

THE DEEP OCEAN ENVIRONMENT

K. O. Gray & P. J. Fritz

Significant Parameters

The following ambient environmental parameters are believed to be pertinent to the location of any underwater structure:

1. Temperature
2. Pressure
3. Bottom Topography
4. pH
5. Eh (oxidation-reduction potential) and H_2S
6. Dissolved Oxygen Content
7. Electrical Conductivity
8. Ocean Currents
9. Salinity
10. Light
11. Rate of Deposition and Thickness of Sediments
12. Viscosity
13. Density
14. Marine Fouling and Boring Animals

In the following paragraphs a brief statement concerning the interrelationships among each of these variables will be made.

Temperature

As the temperature of sea water increases, the rate of corrosion also increases, primarily because the conductivity almost doubles in the range from 0 C. to 25 C.

Warm sea water is very conducive to fouling by organisms. Cold water fouling also occurs, but fouling seems to increase considerably as the temperature rises above 15 C.

No invariable rule can be stated for the relation of temperature with depth, but in most cases temperature is found to decrease with depth. A steep vertical gradient of temperature in an otherwise gently graded sounding is called a thermocline. In the oceans there is a widespread permanent thermocline usually occurring in the depth range from 300 to 3,000 feet, deep enough to be almost unaffected by seasonal variations. In addition, there is often a seasonal thermocline which lies at shallower depths and may disappear entirely during certain seasons. Below the thermocline the sea water temperature can be expected to be generally in these ranges: 3,000 to 10,000 feet,- 34^{o} to 45^{o} F; 10,000 to 37,000 feet,- 32^{o} to 38^{o} F. See Chapter VIII.

Pressure

Hydrostatic pressure in the ocean increases with depth at a rate of about 0.44 psi per foot of depth. This rate is affected by temperature and salinity which also change with depth to varying degrees at different localities. Therefore, if it is necessary to know the true pressure at a particular point in the ocean, it must be either measured in situ or calculated from detailed data on the temperature and salinity gradients.

Pressure will be a critical factor in the design of any large package which must house equipment adaptable with deep sea pressures. Serious consideration should be given to designs which require pressure vessel packaging only for those components which cannot be adapted to a high pressure operating environment. The effects of high pressure on the rate of corrosion and physical properties of material have not been determined. Two high pressure vessels have been designed to investigate this problem of the Naval Civil Engineering Laboratory, but results will probably not be available until the calendar year 1965.

Bottom Topography

Bottom topography varies with geographic location. Most continents have a continental shelf which slopes gently from the shore to a depth of about 100 fathoms where there is an abrupt break in slope; at this point there is a feature known as the Continental Slope which is much steeper and which in turn drops off into the abyssal depths. Beyond the Continental Slope the bottom topography is extremely variable, ranging from deep basins and plains to rugged submerged mountain ranges with a relief range in excess of 6,000 feet. In other words, the sea floor can be expected to be just as varied in topography as the continental land masses.

The Continental Shelf is almost always dissected at fairly regular intervals by submarine canyons which have nearly vertical walls and originate near the shore. Submarine canyons may be continuations of continental river valleys, but many begin off-shore and have no counterpart on land.

The configuration of bottom topography is an important factor in the location of any underwater structure because:

1. Closed basins (those which can be represented on a topographic map by closed contours with a central depression) restrict the circulation of bottom currents and, thereby, tend to promote corrosion by producing stagnant conditions in which H_2S is formed upon oxygen depletion. See Chapter II.

2. Potentially destructive turbidity currents flow down slope following topographic "lows" such as submarine canyons.

For the reasons cited above, underwater structures should not be placed or anchored on topographic "lows." By moving the structure one mile or less, these depressions can often be avoided.

On the other hand, Isaacs, et al, (1963) reports "In our experience moorings on isolated sea mounts (at about 700 fathoms) are much less satisfactory than moorings over the adjacent deep sea floor at 2,500 fathoms. In the Marshall Islands, at least, currents over deep sea mounts seem to be intensified."

Associated with the bottom topography are the problems of the engineering properties of the bottom sediments and the possibility of mud slides. Deep ocean reactors may be associated with sonic transducers which generate shock waves of considerable magnitude. These shock waves might easily precipitate mud slides in areas of unstable sediment deposits.

pH

At the surface, the pH of sea water will usually vary between about 8.1 and 8.3 depending on the temperature and salinity of the water and the partial pressure of carbon dioxide in the atmosphere immediately above the water. Near the shore the pH may drop significantly due to dilution and the chemical effect of mixing with fresh water streams, which are highly charged with decaying vegetation and organic matter and therefore slightly acidic.

Below the surface where direct exchange of carbon dioxide with the atmosphere is impossible, the pH varies with the extent to which the CO_2 content of the water is modified by biological activity. In the euphotic zone (zone of abundant light in which photosynthesis by plants takes place), which is from the surface to a depth of about 250 feet, CO_2 is consumed by plants and higher pH's are usually found; below this the pH decreases to a minimum corresponding in general to the layer of minimum oxygen content and then increases again toward the bottom. Sometimes a sharp drop in pH is noted immediately above the bottom due to the production of CO_2 by organisms, particularly bacteria, on the bottom. At a depth of a few centimeters below the sediment-water interface, oxygen is absent and anerobic bacteria release H_2S, which causes a further drop in pH.

Eh and Presence of H_2S

The oxidation-reduction potential, Eh, is a measure of the ability of the medium to accept or give up electrons relative to the standard hydrogen electrode and may be either positive or negative. Those solutions having high (+) potentials are able to oxidize those with lower potentials.

Values of the Eh in sea water are usually positive being between +200 and +300 millivolts near the surface. With depth the Eh typically remains positive, but may begin to decrease sharply at the sediment-water interface. At a depth of less than 2 meters below the top of the sediments, the Eh usually becomes zero, and below that point the Eh may drop as low as -300 millivolts.

The sharp decrease of Eh with depth in sediments is caused chiefly by the oxidation of organic matter. The position of zero Eh usually marks the first appearance of H_2S. Below that point the H_2S content increases sharply. Zero Eh and the first appearance of H_2S can occur in the sea water overlying the sediments, but more commonly they occur slightly below the sediment-water interface. Consequently, it may prove to be expedient to mount the reactor off bottom to minimize the corrosion problem.

The main factor which controls whether the zero Eh and the first appearance of H_2S are above or below the sediment-water interface is the configuration of the bottom topography. For example, in the case of a closed basin the bottom currents will often go no lower than the "rim" or sill of the basin, and stagnant conditions will exist below that level due to a lack of circulation. Consequently, the zero Eh and first appearance of H_2S are apt to occur in the water above the basin at about the elevation of the sill or slightly below.

Dissolved Oxygen Content

Surface waters are usually saturated with dissolved oxygen. With depth the amount of dissolved oxygen decreases until an "oxygen minimum layer" is reached, which is located below the permanent thermocline at a depth of about 2,000 or 3,000 feet. The exact depth to the oxygen minimum is variable and seems to be a function of density; the minimum usually occurs in water having a density of 1.0272 to 1.0273. Many different combinations of temperature and salinity will give a density of 1.0272. However, the entire water column is usually density-stratified in a uniform manner with the less-dense layers on top; and consequently, there is usually only one layer with a density of 1.0272.

The oxygen minimum layer is thought to be caused by the accumulation and oxidation of organic matter in water having a density which is just adequate to produce buoyancy of sinking organic particles. The organic matter is derived principally from the local surface. Thus, the amount of oxygen deficit is controlled mainly by the local productivity of minute particles of organic matter near the surface and the depth of the oxygen minimum is controlled by the vertical density distribution of subsurface waters.

Below the oxygen minimum layer, the dissolved oxygen content gradually increases until the bottom is reached. Very deep bottom waters frequently have an oxygen content approaching that of surface waters. Upon entering the sediments, the oxygen content drops radically due to the activity of bacteria and bottom dwelling organisms.

The relative low oxygen level (approaching zero in some cases) of the oxygen minimum zone would probably lower the corrosion rate of some steels and increase the pitting tendency of such alloys as aluminum and the 300 series stainless steels. This low oxygen environment might also intensify crevice corrosion activity.

Electrical Conductivity

The conductivity of sea water increases with increased salinity and increased temperature. Variations of salinity in sea water are not great; therefore, changes in conductivity may usually be attributed directly to changes of temperature, except in areas of fresh water dilution where the salinity may drop significantly. The conductivity almost doubles in the temperature range from 0° C to 24° C.

Currents

Except for turbidity currents, the velocity of ocean currents is usually less than two knots. Surface currents such as the Gulf Stream may be as high as six knots (Von Arx 1962). Deep currents (13,000 feet) may approach one knot (Swallow 1961), though more commonly they are on the order of a few tenths of a knot.

The fact that surface and deep currents may be traveling in opposite directions at widely different velocities has been well documented (Fye 1961). The existence of this situation as well as situations where deep (3,000 feet) currents travel in circular paths at velocities averaging 0.33 knots (Parker 1963), indicates that any site for a deep sea installation must undergo a careful oceanographic study to provide the designers with adequate information concerning the forces which may act on the installation.

Many materials form a soft corrosion product on the surface which tends to inhibit further corrosion by serving as a protective layer. If currents are present, the corrosion products may be washed away, thus exposing the material to further corrosion. Currents may also act to aggravate the corrosion situation by constantly renewing the oxygen supply as the corrosion processes consume that locally available.

Probably the most severe environmental hazard to a deep ocean reactor, although one which occurs infrequently, is the turbidity current. A typical turbidity current consists of a thick, dense, turbulent flow of rocks, sand, and mud, which may be initiated by a minor earth tremor. Only a very gentle slope is required to maintain flow. Turbidity currents usually move rather rapidly down a submarine canyon until the mouth of the canyon is reached. There the current spreads out onto a deep trough or an abyssal plain and begins to lose velocity.

In 1929 six transatlantic cables were broken successively from north to south by some unknown phenomenon later interpreted as a turbidity current. Knowing the distance between cables and the time between breaks, the velocity of the current was easily computed (Heezon et al, 1954). Starting with an initial velocity of about 55 knots, the current flowed southward for about 300 nautical miles, and the velocity decreased uniformly to 12 knots at the point where the last cable was broken.

At the Scripps Institute of Oceanography, Inman and others have measured turbidity currents in Scripps Canyon located just off shore from the Institute's pier. The evidence gathered so far would indicate that turbidity currents may be seasonal, occurring in late winter or early spring once each year. Longshore currents in the oceanside cell move southward carrying sand and silt to a point where the current is diverted due to the presence of a minor peninsula. Sand and silt accumulate on the north side of the minor peninsula until a critical mass of about 200,000 cubic yards is reached. Then by a process which Inman calls "spontaneous liquifaction" usually triggered by a very minor earth tremor, the mass of sand and silt suddenly becomes mobile and starts to slide down Scripps Canyon. The flow is maintained by the presence of a continuous slope for a distance of about 30 miles until it reaches the bottom of the broad San Diego trough. The slope is about 14° near the head of the canyon, 5½° near the middle, and about 4° at the mouth.

Very little is known about turbidity currents, but the evidence gathered to date would suggest that there may be many small ones occurring every year within 50 miles of shore, whereas the larger ones similar to the Grand Bank current are rare but may occur anywhere in the ocean.

Kuenen (1950), considering the effects of slumping of soft sediments at the head of a submarine canyon, states the following: "Assuming a thickness (of sediments) of 4 meters on a slope of 3° and a density of 2, the computed velocity is 3 meters per second. Such a current can carry along boulders weighing some 30 tons".

Off the California coast, turbidity currents are thought to occur periodically in submarine canyons such as Hueneme, Mugu, Santa Monica, Redondo, San Pedro, San Gabriel, Dume, Newport, Coronado, La Jolla, Santa Catalina, Tanner, and Santa Cruz.

Kuenen (1950) further states "At Redondo, a slide was actually witnessed from the pier that had recently been extended to the head of Redondo Canyon. Numerous people fishing along the pier with a calm sea and no wind felt their leads being pulled out to sea and had to put out more line to get bottom. After a short interval, boiling masses of mud appeared in the water. In about an hour the deepening had ceased, but not until depths had increased from 3 to 12 m. Shepard also points out that where great masses of sand and silt are yearly introduced into the heads of canyons close inshore, slumping of some sort must be continually keeping these depressions from being filled in.

There can be small doubt that the movement in these cases was of the nature of slumping. But some features indicate that the slumps tend to change to turbidity currents. More than once where sudden deepening was actually witnessed, currents have been seen to flow into the head of the canyon. This proves that a large volume of water was passing down the canyon away from the coast. If only sediment had taken part in the movement, no extra water would have been drawn into the canyon. Thus, evidence is found that the slumping results in a flow of watery mud or muddy water".

Because gravity is the motivating force, the flow always follows the "valleys"; consequently, it appears advisable that submarine canyons be avoided.

Because submarine canyons are frequently rather narrow, it would usually be possible to avoid them completely without changing the proposed location by more than 1/2 mile.

Salinity

The salinity of sea water is usually between 33 and 37 parts per thousand. The surface salinity may be considerably less than these average values, particularly in regions where there is dilution by fresh water streams, heavy rainfall, or in the high latitudes where melting of icebergs occurs. The average salinity of sea water is usually taken to be 35 parts per thousand.

In many cases the bottom waters are slightly more saline than the intermediate and surface waters because density increases with salinity and the oceans tend to be density-stratified, the denser waters being located at the bottom. However, density is also a function of temperature, and a mass of very cold water with a low salinity may be more dense than a mass of warm water with a higher salinity. Consequently, the mass with the higher salinity overlies the one with the lower salinity. These exceptions are numerous enough to make any generalization of these relationships invalid.

Since conductivity increases with salinity, corrosion problems are accelerated at higher salinities. However, the salinity of sea water is nearly constant under open sea conditions, and the slight variations which may be noted locally will usually have a negligible effect upon the rate of corrosion.

Light

The penetration of light in the sea is mainly a function of the amount of suspended sediment and organic matter in the water, which in turn is at least partly dependent upon agitation and currents. In the clearest water, light may be perceptible to a depth of 2,300 feet, in average open ocean water to 1,000 feet, and in agitated coastal waters to 200 feet or less.

Fouling by marine organisms decreases below the zone of light. Furthermore, the oxygen content is dependent mainly upon organic activity and the oxygen minimum layer usually occurs below the zone of light, where plants cannot live, because plants take in CO_2 and release oxygen to the water.

The amount of sediment in suspension is chiefly a function of the distance from shore, the number of streams emptying into the ocean in the local area, the types and amounts of particles being carried by the streams, and the velocity of the currents carrying the sediment load.

Rate of Deposition and Thickness of Sediments

In deep basins off the California coast, sediment accumulates at the rate of about one inch per 84 years (Shepard, 1948, p. 308). In the Gulf of California, the rate is one inch per 25.4 years (Shepard, 1948, p. 308). Locally the rate of accumulation could be much faster due to the proximity of a stream discharging sediment into the ocean. Another factor which would accelerate accumulation is the presence of a turbidity current, which could discharge a large volume of sediment into a deep trough or abyssal plain at a very rapid rate, but for a short time.

It is impossible to predict the thickness of loose mud at a particular anchor point. This thickness must be determined by an "on site" investigation.

In deep ocean muds the maximum particle size is also largely a function of the distance from shore. A typical deep sea mud is expected to be composed mainly of clay particles having an average diameter of from 1 to 5 microns. Globigerina oozes are common on the floor of the deep ocean about 100 miles off the east coast of the United States and are made up of tiny shells of calcium carbonate secreted by one-celled marine animals. The shells are mostly above 75 microns in size and comprise at least 30% of the volume of the mud.

The porosity (ratio of volume of voids to total volume in situ) of unconsolidated muds is usually about 50%. Specific samples taken in the Pacific ocean have run as high as 80%. At a depth of 500 feet below the surface of the mud, the weight of the overlying material compacts the mud, reducing the porosity to as little as 33%.

Viscosity

Viscosity increases gradually with an increase in salinity and more rapidly with a decrease in temperature. The viscosity almost doubles in the interval of a temperature drop from 25 to 0° centigrade.

Density

The density of sea water is a function of temperature, salinity, and to a lesser degree pressure. At present, there is no direct method for measuring density in situ. Calculated values of in situ density depend upon the empirical knowledge of saline contraction, isothermal compressibility, and the coefficients of thermal expansion of sea water.

Because of non-linear interaction among them, each is an imperfectly known function of ambient temperature, salinity, and pressure.

Most recent investigators have expressed the opinion that instead of a small but steady increase of density with depth, the deeper water more commonly consists of multiple layers. Each is in complete neutral adiabatic equilibrium, with the heaviest layer at the bottom.

CHAPTER II

MARINE FOULING AND BORING ANIMALS

J. S. Muraoka

Fouling, or the growth of marine animals and plants on the surface of submerged objects, effects the efficiency of propulsion of ships, interferes with the mechanisms which actuate mines, reduces the efficiency of under-water accoustic devices, reduces the flow of water when fouling occurs in pipes and conduits, may injure protective coating resulting in a localized break which may lead to serious pitting and has many other detrimental effects.

In general the heaviest fouling occurs on the surface of objects submerged in shallow coastal waters and also in harbors where there are abundant plant and plankton available as source of food. The temperature of the water also has great influence on fouling activity. The attachment season is more limited in temperate than in tropical waters. For many groups the attachment season lasts the year round in the tropics while confined to the summer months in temperate waters. (Woods Hole Oceanographic Institution, 1952.)

Fouling and boring animals are also known to occur in deep waters as well as in shallow waters.

The character and quantity of the deep water fouling community is frequently different from that found at the surface because of the difference in water temperature, availability of food, darkness, salinity, dissolved oxygen content, hydrostatic pressure, etc. At the surface, green, red, and brown algae predominate and extend to depths of 100 feet or more. Below the zone of algae, animals such as barnacles, mussels, bryozoa and tube worms predominate to a depth of 200 feet or more. Below this depth, hydroids are generally the principal fouling organism. Hydroids are classed under Phylem Collanterata which also includes anemones, corals and jellyfish.

In a recent study of marine fouling and corrosion in the Tongue of the Ocean fouling organisms were found attached to a mooring line in moderate to severe amounts in the upper 300 feet, slight to moderate from 300 to 900 feet, and slightly thereafter to about 6,000 feet. A boring mollusk, Xylophaga cp, was observed boring into wooden test panels exposed directly on the bottom. (DePalma, 1962).

Marine Bacteria

Marine bacteria are found in sea water and in bottom sediments from shallow depths to the deepest portion of the sea. The greatest number have been found in coastal waters where the greatest abundance of plant and animal life is also produced; however, the greatest density of bacterial population is found on the bottom, where millions of bacterial cells per gram of wet mud may occur. ZoBell and Morita (1955) found millions of viable bacteria per gram of sediments taken from depths exceeding 33,000 feet on the Danish Galathea Deep-Sea Expedition. Because marine bacteria are able to live in varied marine environments and can utilize various material for growth, they are one of the major biological agents for deterioration in sea water and in marine sediments.

The marine sulfate-reducing bacteria which produce hydrogen sulfide as the end product of their metabolic process have assumed particular significance since it was discovered that they are agents of deterioration of organic as well as inorganic materials. (Starkey 1960 and Scott 1960.) The sulfate-reducing bacteria are found abundantly in the mud and on forked or rusting surfaces of submerged objects.

Fouling and Nuclear Reactor

A nuclear reactor placed on the deep ocean floor will produce considerable heat warming the above body of cold water and perhaps the bottom sediment directly underneath the reactor. The increase in the water temperature may tend to increase the fouling and boring animal activity as well as the sulfate-reducing bacteria inhabiting the sediment.

It is anticipated that certain sections of the reactor may have optimum surface temperatures for the attachment of fouling communities. If such an area happens to be the heat exchanger unit of the reactor, any fouling will effect the efficiency of the heat exchange unit which in turn will affect reactor operation and efficiency. There is no known information on the effects of warmed solid surfaces in promoting or inhibiting marine growth.

CHAPTER III

CORROSION PREVENTIVE MEASURES

J. B. Crilly

A submerged reactor in the deep ocean would almost certainly have exposed metal surfaces subject to varying rates of deterioration and corrosion, depending upon temperature, salinity, and the presence of dissimilar metals. The severity of the problem is discussed in Chapter I. For a short life of a few years, it is possible that experience will show that a nominal extra provision of metal thickness will be sufficient. Until experience is accumulated, coatings to minimize the problems as discussed below seem necessary; an alternative is the surfacing or fabrication of critical parts from highly corrosion resistant materials.

Galvanic corrosion and stress corrosion will, according to Owen and Ruble (1960) and Staehle, et al (1958), be the primary problems with exposed metals in the ocean depths. Fouling of heat exchanger surfaces may be another problem if they are below 125 F. Corrosion due specifically to bacteria, or to hydrogen sulfide produced by them, may prove to be another problem to be controlled.

Prevention of galvanic corrosion has been studied by the Navy (Saroyan and Smith, 1957; and Aeronautical Material Laboratory, 1962) and some tentative processes have been outlined. The best solution is, of course, choice of materials to avoid formation of corrosion couples by dissimilar metals. Where this is not possible, steps may be taken to provide breaks in the path of the corrosion current by use of insulating gaskets. Galvanic corrosion studies in Great Britain are described by Evans and Rance (1955), and Zurbrugg (1958). Other work, on alloy plating for protection of aluminum is described by Pinkerton (1959).

Economic factors often dictate the use of cheaper, more common alloys in a near-surface ocean environment, even though a protective paint or coating system must be applied to reduce the rate of corrosion of the metal. Similar considerations may well apply to the use of metals in the ocean depths. Except for the unknown effects of pressure on coatings, problems in the use of coatings here are similar to those encountered near the surface. They may, in fact, be less severe because of lack of ultraviolet light, a decreased oxygen supply, and uniform lower temperatures. On the other hand, the presence of sulfate-reducing bacteria in some ocean bottom areas may produce increased corrosion rates. Three thousand psi (the pressure at 6000 ft.) is approximately the order of magnitude of the force required to break a moderately good adhesive-to-metal bond, but such pressures will probably not affect the service life of coatings to any great extent.

This Laboratory will obtain corrosion rate information for many different metals and alloys exposed to the ocean depths for periods of one or more years under an existing task. At the same time that test specimens are used to supply this information, the behavior and protective qualities of several coating systems will be determined. Systems selected for the first phases of this work have performed well on steel piling exposed for 2-1/2 years to an intertidal ocean environment at Port Hueneme, California. Parameters to be considered in evaluating coating failures and/or metal corrosion include surface preparation, adhesion of coating to metal surface, usefulness of special pretreatment primers, water permeability of coatings, development of concentration cells undercutting coatings, and effectiveness of inhibitive pigments. Laboratory pressure systems in which the ocean floor environment can be simulated will be very useful for the investigation of pressure effects under controlled conditions.

As this deep ocean work progresses, answers obtained will point the way to new areas for investigation through in situ testing and evaluation. If coatings deteriorate as the result of fouling or bacterial attack, these factors will be considered in selecting or developing improved protective coating systems. Problems of fouling are not new although the organisms to be guarded against doubtless will be (Ohr, 1960; Fitzgerald, et al, 1947; Cranmer, 1957; and Greathouse, 1956). Antifouling coatings on submerged surfaces with service life of more than two years are available. The behavior of metal substitutes such as plastics will be studied along lines laid down by workers at David Taylor Model Basin, where filament wound and laminated plastics have been investigated for use in deep submergence pressure hulls (Buhl et al, 1961; Eakins et al, 1960; and Material Laboratories, New York Naval Shipyard report, 1957). Use of these materials might greatly reduce the weight of a power package, thus simplifying emplacement and foundation problems. Several coating systems for submerged steel, aluminum and glass reinforced plastic surfaces have been investigated by Dear (1957) and Anderson (1958).

Reinforced plastic coatings for aluminum and for steel have been studied by Phelps (1962a and 1962b). Coatings for external piping and faying surfaces of submarines are protected by application of pressure sensitive adhesive plastic tapes described by Material Laboratories, New York Naval Shipyard (1960). The Bureau of Ships Technical Manual (NavShips 250-000), Chapter 19, paragraphs 121-123, gives detailed directions for painting submarines. Pressure hull shell plates are coated with primer formula 117. Intermediate and topcoats are vinyl-based paints, formulas 119 and 121, and others for special surfaces.

If coating systems prove only partially satisfactory for the protection of cheaper alloys, used because of economic or structural considerations, it will be desirable to investigate the feasibility of cathodic protection as a method of control, supplemental to the use of protective coatings. Such a combination is frequently used on metal structures or systems exposed to ocean environments at and below the surface. Cathodic protection might prove to be a more satisfactory solution to the corrosion problem than protective coatings in cases where anchor chains or cables are used to secure a structure to the ocean bottom or to maintain physical contact with the surface. In such investigations the effect of high pressures on the flow in sea water of electrical current accompanying cathodic protection would require study. So also would the effects produced by pressure, temperature and microbial conditions at great depths on corrosion potentials of various metals, with or without protective coatings. To measure and study corrosion potentials it will be necessary to determine the effect of pressure on different half cells that might be used as reference electrodes. Impressed current systems would be considered, with the reactor supplying the current. Systems using the most promising types of metals for sacrificial cathodic protection could be designed, fabricated and tested in situ, should this appear desirable. The latter system is much simpler and less likely to fail than the former. Against this must be balanced its limited life without replacement of the anode. The problem of controlling an impressed current system might be avoided by proper choice of current source to provide a constant voltage device essential to satisfactory protection. Self-recording instrumentation would be installed to record the potentials produced in various locations of a structure or system being protected. These potentials would be related to any corrosion that might occur and to any changes in the deep ocean environment that might favor such corrosion. Parameters of concern in this environment were discussed in Chapter I. To measure many of these parameters in situ, new techniques and instrumentation will have to be developed.

CHAPTER IV

FOUNDATION CONSIDERATIONS FOR AN OCEAN FLOOR NUCLEAR POWER SOURCE

R. J. Smith & K. J. DeBord

Introduction

The foundation engineering problems involved in contemplating the placement of a nuclear power source on the floor of the deep sea differ but little from those of installing any other type of large or heavy object in this particular environment, with the possible exception that because of cooling requirements no part of the generating device itself should be subject to burial. This latter qualification is primarily one of design.

There have been few opportunities to observe the behavior of larger objects placed on the bottom in deep water, and comparatively little is known of the support problems that exist relative to the deep sea soils. Some predictions have been made, however, on the various ways in which this operation will require treatment different from the normal land procedures by Richards (1961), Richards (1962), Smith (1962), and in studies by industrial groups (A. D. Little, 1962). Measurements of some of the physical properties of ocean floor soils are now being made by several groups in both industry and government, and a few recommendations have been made on how best to conduct actual load tests in these deep waters.

The marine area of the world is made up of many differing environments, as varied as those observable on land. Summarily, it is possible to broadly divide this realm into the shelf regions as occur on the margins of the continents and as are characterized by water depth of less than 600 feet, and the true oceanic areas far from shore having depths approximating a 12,000 foot average.

The shelf regions, that constitute some 8 percent of the total area, may be considered as readily accessible and many types of activities requiring an understanding of the physical characteristics of the bottom sediments are currently being carried on here. Sampling and testing operations in these shallower waters can be relatively easily accomplished through use of techniques closely akin to those applied on land. In addition, this near-shore shallow shelf is the place of deposition of the coarser land-derived sands and silts, which themselves inherently offer insignificant problems of support in comparison to those of the soft deep-water muds and oozes.

The deeper oceanic areas that comprise the other 92 percent of the marine world show a different picture as to potential foundation engineering problems relative to emplacement of a nuclear power source. Here a general lack of information on physical properties of the bottom soils combines with the difficulty of securing undisturbed samples for testing far enough into the bottom to enable satisfactory design. These adversities are compounded by the fact that these deep sea areas are largely further removed from continental detritus sources, and as a consequence represent zones of deposition of only the finest of the clayey soil constituents and organic-derived oozes. The most unfavorable of all possible foundation conditions are therefore found here. For the purpose of this present analysis, therefore, emphasis is placed primarily on the problems of these more unfavorable deeper-water areas further from shore, for this is where the major sea floor foundation problems exist. Once the most effective ways to deal with these deeper regions have been learned, shelf areas should offer but few challenges.

The ensuing discussion is comprised essentially of three subject areas. The first and second of these pertain to the two usual foundation engineering considerations, namely the bearing capacity of the soils and possible extent of settlement that may be anticipated. These are followed by a presentation of the procedural steps now believed necessary for proper evaluation of a given bottom site as a potential location for an underwater reactor.

Bearing Capacity

It is axiomatic that the bearing capacity of the soils required for support of a nuclear power source placed on the bottom varies with the shear strengths of the sediments present. Such is of course true for any object placed on the sea floor, as well as on land. The estimation of bearing capacity limitations, therefore, depends on measuring the shear strengths in the areas of interest.

Comparatively few determinations of shear strength of the sea floor materials have been made on which to base an opinion as to average or typical conditions that might be anticipated in this region. It has become apparent, however, that the variations in undersea topography that occur exert a pronounced influence on both type and strength of the sediments present in a given locale. In places having a higher relative relief, as for example on some seamounts and submarine ridges, very hard and sometimes old rock has been found exposed directly at the water interface. A search for possible sites for placing heavy objects, such as a reactor, on the sea floor would therefore indicate these points of higher topography as logical first choices. The basinal areas of the sea, and particularly those exhibiting markedly smooth planner surfaces, have everywhere been found comprised of the softer sediments of high water content and extremely low strength. The factors other than topography that act to control supporting capabilities are presently not well understood. Doubtlessly original composition exerts much influence, but later diagenetic changes are also locally able to greatly increase hardness.

Determinations of sea floor soil strength are limited in number. One of the first to attempt such a measurement was Arrhenius (1952) on his samples from the Eastern Pacific. For this work the Swedish fall-cone method of determining the strength was used; however, the difficulties of satisfactorily converting these values to standard shear strength figures as currently applied in foundation design limits the usability of his results. The investigations undertaken by Richards (1961) and Richards (1962) represent the first really comprehensive examination of the physical characteristics of sea floor materials following the direction of more standard soil mechanics analytical techniques. Samples from both Atlantic and Pacific oceanic areas were examined in this program. Moore (1962) lists what appear to be quite valid determinations from cores secured from both deep and shallow North Pacific waters. Inderbitzen (1963) has recently published results of shear strength readings on shallower water cores from immediately off of San Diego. At present NCEL is carrying on a comprehensive program of testing of cores secured by Naval Oceanographic Office ships from deep waters of the eastern North Pacific that is yielding abundant data on the properties of these sediments and their variations.

From the above sources it is possible to compile a number of determinations of shear strength that may be considered as typical for deep sea areas. These figures have been assembled for presentation as Table I of this report. Within this table the locations where the cores were secured and their water depths are given. Shear strength is listed as cohesion, measured in psi, in that primarily clayey soils having low friction angles are involved in each instance. It is believed that at least some of the values shown are valid measurements for their respective areas of origin. The testing of sea floor cores done to date has demonstrated that within each core the shear strength values generally increase with depth into the bottom. The lower readings found in the upper portions of each core are those included in the Table I. In all likelihood some of the readings given were obtained from samples subjected to excessive disturbance subsequent to collection, as well as presumably to at least some desiccation. Most of the oceanographic coring tool varieties in current use have unsatisfactory dimensions when compared with those commonly accepted in soil mechanics as producing samples of undisturbed character. Further, in most of the instances the cohesion was measured by use of the Laboratory vane shear device, which is still subject to some controversy as to the validity of resulting shear strength figures. As a result of questions arising from the means of converting the fall-cone readings of the Swedish expedition to values of cohesion, this data has not been included.

The ability of a foundation configuration to support a certain loading condition without undergoing shear failure is dependent both on the dimensions of the given foundation involved and the shear strength of the soil on which it rests. The general formula derived by Tschebotarioff (1951) defining the ultimate unit load for clayey soils is:

$$P_{max} = 5.52c \left(1 + 0.38 \frac{h}{b} + 0.44 \frac{b}{L}\right) \quad (1)$$

where c = cohesion or shear strength of soil

h = depth below soil surface

b = width of footing

L = length of footing

In the case of a square footing, b is equal to L. Where the footing is emplaced directly at the ground surface, the value of h is zero. Under these conditions the above relationship reduces to:

$$P_{max} = 7.95c$$

The studies of Skempton (1951) have shown that the ultimate unit load for a circular footing under similar conditions may be expressed by:

$$P_{max} = 6.57\ c$$

in which c again represents the cohesion of the soil.

For purposes of the preliminary considerations of this report, the assumption may be made that a reactor power source designed for deep sea installation is likely to have either a square or circular footing, and that the device and its foundation would be lowered as a unit and placed directly on the sea floor surface. On this basis the above equations enable estimates to be made of footing sizes necessary to support various loads. Figure 1 and Figure 2 therefore represent plots of these relationships for different loads and soil strengths for both a square and circular footing. If the weight of the reactor may be estimated, and the shear strength of the bottom soil measured, it is thereby possible to determine a minimum footing width or diameter required. It is of interest to compare the range of values of cohesion recorded from sample testing as compiled in Table I with those included on the Figures in relation to variations in required footing dimensions. It should be pointed out that these charts are not intended to be used as a basis for design, but only as an indication of general requirements for the deep sea floor situation. In practice, a safety factor of at least three to four should be applied to such values.

Settlement

When a reactor power source or other type of load is placed on the sea floor and shear failure does not occur, it may be anticipated that at least some settlement will take place. Several fairly standardized techniques have been developed to enable estimates to be made as to the extent of this movement. By one such procedure:

$$\text{Settlement} = \frac{\varepsilon_o - \varepsilon_f}{1 + _o} \times H \qquad (2)$$

where ε_o = original void ratio

ε_f = final void ratio

H = initial consolidating thickness

In the application of the above relationship to sea-floor conditions or relatively uniform vertical lithology, the soil section beneath the proposed point of loading is divided into a series of uniformly-spaced horizontal layers, with H representing the thickness of each zone. The original void ratio ε_o is obtained by laboratory measurement. The final void ratio ε_f is taken from experimental consolidation curves prepared in the laboratory. The final loads acting on each of the horizons used to determine ε_f is calculated by use of the Newmark (1935) influence chart. The total settlement is obtained by adding the increments for each of the horizontal layers. In that this follows accepted procedures, and each core material studied exhibits its own typical consolidation curve, it is not necessary or possible to further generalize on potential settlements using this approach. Each individual case of soil and imposed loading is unique.

The settlement may also be estimated through application of the compression index, a value which may be obtained from the Void Ratio-Pressure curve of the soil by:

$$C_c = \frac{\varepsilon_o - \varepsilon_1}{\log \frac{P_1}{P_o}} \qquad (3)$$

An approximate value of the compression index can be determined by the relationship:

$$C_c = 0.009 \text{ (Liquid Limit - 10)} \qquad (4)$$

TABLE I. Some typical values of cohesion for sea-floor soil samples.

Position		Depth	Cohesion	
Latitude N.	Longitude W.	Feet	psi	Source
30°	75°	4,080	0.79	Richards (1962)
30°	75°	6,600	0.44	" "
35°	5°	4,320	0.34	" "
35°	5°	2,400	0.29	" "
35°	5°	3,720	0.37	" "
35°	10°	3,720	0.06	" "
35°	10°	3,480	0.11	" "
40°	65°	7,440	0.42	" "
40°	65°	8,040	0.41	" "
40°	65°	7,980	0.11	" "
40°	65°	7,920	0.30	" "
60°	5°	3,660	0.53	" "
60°	5°	3,660	0.66	" "
60°	5°	4,800	0.09	" "
03° 42.5'	114° 09'	15,120	0.188	Moore (1962)
13° 29.5'	108° 33.5'	12,200	0.077	" "
32° 27'	120° 41'	12,070	0.169	" "
32° 35.4'	117° 20.6'	417	0.377	" "
32° 36.8'	117° 21'	587	0.115	" "
32° 36.8'	117° 21'	600	0.217	" "
32° 37.4'	117° 20.4'	433	0.102	" "
32° 37.5'	117° 18'	276	0.057	" "

TABLE I. Some typical values of cohension for sea-floor soil samples (cont'd)

Position		Depth	Cohesion	
Latitude N.	Longitude W.	Feet	psi	Source
32° 38'	117° 35.5'	3929	0.252	Moore (1962)
32° 38.2'	117° 20.2	325	0.205	" "
32°38.5'	120° 24'	12,000	0.165	" "
32° 38.9'	117° 19'	276	0.108	" "
32° 40'	117° 30.5'	2919	0.294	" "
32° 40'	117° 30.8'	3280	0.211	" "
32° 40'	117° 33.4'	3746	0.102	" "
32° 40'	117° 35.5'	3847	0.112	" "
39° 56.2'	158° 38'	18,670	0.116	" "
42° 30'	162° 08'	17,710	0.084	" "
43° 16'	163° 40'	17,710	0.103	" "
47° 10'	165° 45'	16,970	0.159	" "
32° 33.8'	117° 29.0'	3936	0.153	Inderbitzen (1963)
32° 36.1'	117° 21.2'	607	0.256	" "
32° 36.6'	117° 20.1'	525	0.096	" "
32° 36.7'	117° 20.6'	541	0.102	" "
32° 36.8'	117° 21.1'	577	0.230	" "
30° 43.3'	120° 49.9'	12,418	0.140	NCEL
30° 44.5'	120° 39.7'	12,536	0.460	"
31° 05.8'	120° 41.7'	12,267	0.304	"
31° 15.1'	120° 41.2'	12,280	0.300	"
31° 34.1'	121° 01'	12,579	0.595	"

TABLE I. Some typical values of cohesion for sea-floor soil samples (cont'd)

Position		Depth	Cohesion	
Latitude N.	Longitude W.	Feet	psi	Source
31° 32.5'	121° 29.1'	12,628	0.330	NCEL
31° 26.1'	121° 27.9'	12,658	0.770	"
34° 38.5'	122° 44.9'	13,107	0.326	"
34° 36.3'	122° 22'	12,297	0.256	"
34° 42'	121° 57.3'	12,890	0.166	"
34° 53'	122° 14.3'	12,904	0.262	"
35° 05'	122° 14.5'	14,156	0.186	"
35° 12.8'	122° 00.5'	9778	0.375	"

Once the value of the compression index has been obtained the settlement may be calculated by:

$$\text{Settlement} = \frac{C_c}{1 + \varepsilon_o} H \log_{10}\left(\frac{P_o + \Delta p}{P_o}\right) \qquad (5)$$

where C_c = compression index

ε_o = initial void ratio

ε_1 = void ratio corresponding P_1

H = thickness of compressible layer

P_o = initial pressure

P_1 = a pressure higher than P_o

Δp = change in pressure due to load

In using this procedure again the several horizontal layers of thickness H must be delimited beneath the point of load application, and the value of Δp computed from Newmark's chart. There have been a few determinations made as to values of the compression indices for sea floor core materials both from consolidation measurements and by the Atterberg Limit relationship. Some typical C_c values are listed in Table II from various parts of the world. The use of the compression index method of estimating settlement again represents a situation where each load, area of application, and C_c is unique for the individual circumstance. It is therefore not possible to make generalized estimates of expected settlements without firmly defining these parameters.

A close look at the character of some of the softer materials present on the sea floor, however, suggests that there might be some question as to the applicability of these standard settlement estimating techniques just described. Analyses have shown that natural water contents of many of these soils are frequently well above their liquid limits. This means that once these materials have been subjected to sufficient disturbance, they fall by definition into the category of viscous liquids rather than solids and in some respects should be so treated. It would appear as if the process of placing a heavy reactor package on the bottom is apt to be a sufficient jar to disrupt the original soil structure. As a less favorable alternative to the standard settlement approaches, therefore, some areas of the sea must be considered as floored by semi-fluid materials, and the foundation designs must at least partially be based on a buoyancy factor.

TABLE II. Representative values of C_c from sea-floor core material

Position		Depth		
Latitude N.	Longitude W.	Feet	C_c	Source
30°	75°	4080	0.23	Richards (1962)
30°	75°	6600	0.37	" "
35°	5°	4320	0.43	" "
35°	5°	2400	0.54	" "
35°	5°	3720	0.44	" "
35°	10°	3720	0.61	" "
35°	10°	3480	0.46	" "
40°	65°	7440	0.22	" "
40°	65°	8040	0.32	" "
40°	65°	7980	0.52	" "
40°	65°	7920	0.54	" "
60°	5°	3660	0.32	" "
60°	5°	3660	0.35	" "
60°	5°	4800	0.71	" "
35° 12.8'	122° 00.5'	9780	0.63	NCEL
35° 05'	122° 45'	14,160	0.86	"
34° 53.5'	122° 45'	13,020	0.88	"
34° 55'	122° 27.5'	13,020	0.76	"
34° 53'	122° 14.3'	12,906	0.82	"
34° 55'	121° 59'	12,300	0.93	"
34° 42'	121° 57.3'	12,894	0.85	"
34° 36.3'	122° 22'	12,300	0.80	"

TABLE II. Representative values of C_c from sea-floor core material (cont'd)

Position		Depth		
Latitude N.	Longitude W.	Feet	C_c	Source
34° 38.5'	122° 44.9'	13,110	1.03	NCEL
34° 40'	123° 00'	13,320	0.75	"
31° 26.1'	121° 27.9'	12,660	0.87	"
31° 32.5'	121° 29.1'	12,630	0.61	"
31° 34.1'	121° 01'	12,582	0.66	"
31° 15.1'	120° 41.2'	12,282	0.87	"
31° 05.8'	120° 41.7'	12,270	0.88	"
30° 44.5'	120° 39.7'	12,540	0.78	"
30° 43.3'	120° 49.9'	12,420	0.76	"
31° 22.8'	121° 48.8'	13,200	0.79	"

It is readily apparent that the most favorable support configuration in dealing with a fluid bottom soil would be some type of raft, with sides of sufficient height to enable the structure to essentially float on the bottom without foundering. From the point of view of buoyancy, it is possible to estimate the maximum settlement to be expected under such circumstances. The diagram of Figure 3 shows the forces acting on such an object to be:

$$F_v = 0; \qquad F_2 + Wt - F_1 = 0 \tag{6}$$

$$\gamma_w As + Wt - \gamma_s As = 0$$

$$Wt = As\,(\gamma_s - \gamma_w)$$

$$S = \frac{Wt}{A\,(\gamma_s - \gamma_w)}$$

where Wt = total weight of reactor and support

A = area of bottom of foundation

γ_s = average soil density

γ_w = water density

F_1 = weight of displaced soil

F_2 = weight of water below interface

s = settlement

In the above equation the buoyant force due to the water displaced by both the reactor and the structural materials themselves has been neglected in view of their comparative high specific gravities, and this neglected buoyant force provides a small added factor of safety.

The settlement relationship based on buoyancy as determined in the above paragraph has been plotted in Figure 4 and Figure 5 showing the maximum settlements that might be anticipated for raft foundations of respective square and circular plan. The total weight of reactor and support and the footing dimensions are varied. The assumption has been made that the average bulk density of the soil involved is 1.4 gm/cc, a value that appears reasonable from the measurements made to date. As an example of the method of using Figure 4, a total load of 200 kips on a footing of 40 foot width would produce a settlement of approximately five feet.

Site Investigation Procedures

In spite of the fact that relatively few operations involving heavy objects and requiring knowledge of the strength of the sediments have been carried out present development of oceanographic techniques together with those of use in soil engineering enables the enumeration here of the several stages involved in a site investigation for purposes of installation of a nuclear power source.

It is important to review all of the bathymetric charts and oceanographic reports pertaining to an area of particular interest for such information as to the bottom conditions. The compositional data found in such sources, however, must be used with caution. On the basis of present knowledge it is impossible to convert a compositional determination to a reliable strength designation. Bathymetric charts usually enable study of the gross submarine topographic features that are frequently important in site selection questions. As a rule of thumb, the more irregular the topography the better the supporting characteristics of the bottom soils.

Prior to putting an object such as a nuclear reactor on the bottom, a fairly detailed bathymetric chart of the immediate area of interest must be prepared. The bottom contouring task is most satisfactorily done with one of the various types of precision depth recorders, covering the location with a series of profiles arranged in the form of a grid. A fairly standard set of procedures have been developed to convert these profiles over to the finished chart. It is frequently advantageous to consider the combining of this bathymetric mapping with a sub-bottom study, for both results may be obtained from the same instruments. Not only would such sub-bottom records be of use in predicting foundation conditions, but they permit taking advantage of sea floor variations in laying out a sampling program.

The details of the footings for an object to be placed on the sea floor are based on the results of physical tests made on samples secured with oceanographic coring tools of either the gravity or piston type. Figure 6 shows the use of a gravity typed corer, this particular device having a total weight of approximately 400 pounds and a barrel of 2-1/2 inch diameter. In planning a core sampling program it is necessary that a sufficient number of samples be collected from a broad enough area to define all potential supporting conditions for an object to be placed on the bottom. After the core material has been collected, great care must be used in subsequent handling to reduce the disturbance to a minimum. It is advantageous that testing be conducted as soon after collection as possible, in that some soils undergo significant changes in properties when stored for even very short periods of time.

The physical tests of the samples are in general those normally used for determination of the bearing capacity and settlement in soil mechanics analysis. Making tests on some samples of very high water content in instances necessitate the use of unique measuring techniques, for example the shear strength requiring use of the laboratory vane shear device. In most cases these tests are each made at specific intervals of the length of the core. It is advantageous to prepare a lithologic log as an accompaniment to the physical testing program in order to best interpret the results.

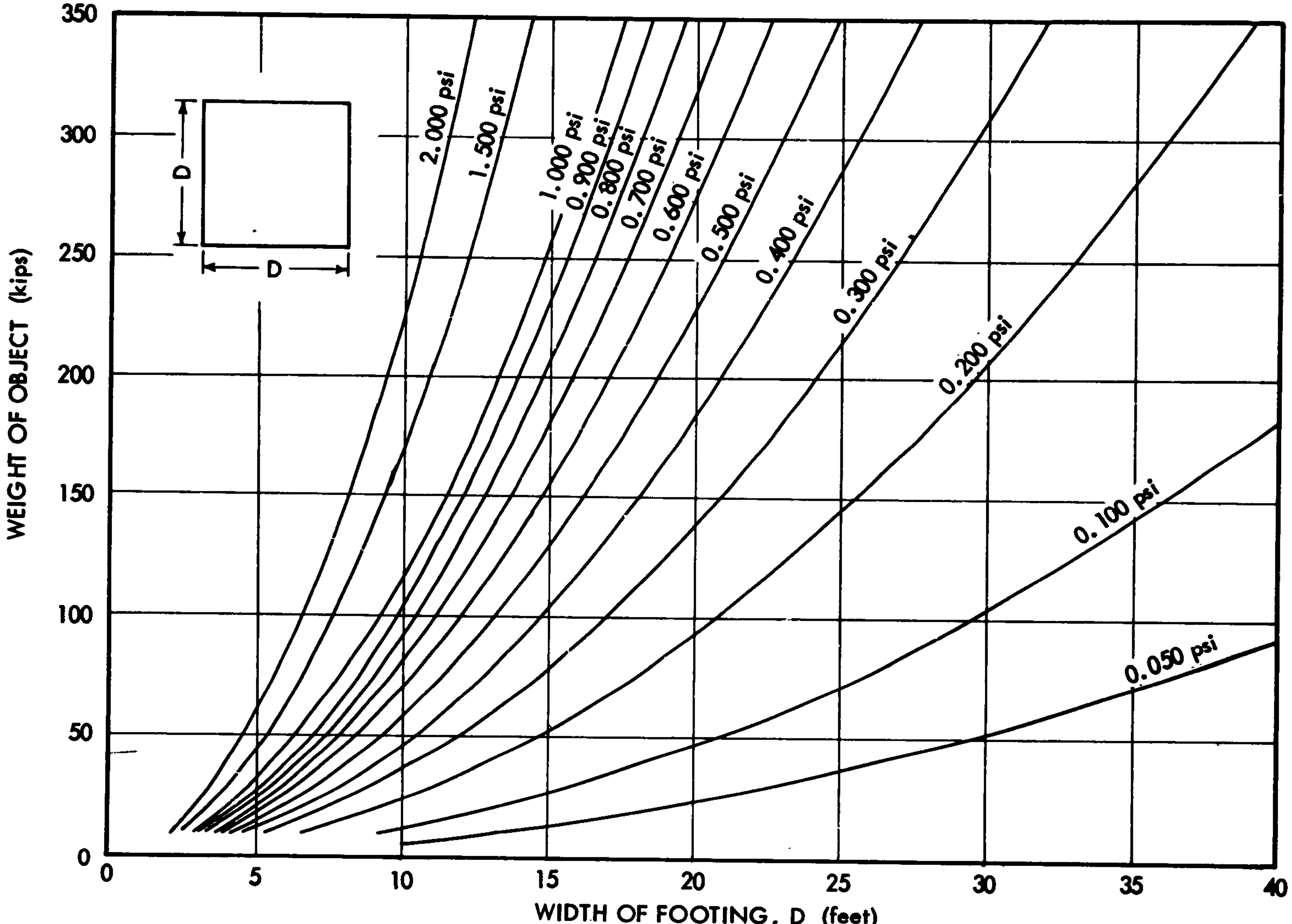

Figure 1. Plot of Width of Square Footing Required to Support Reactors of Varying Weights on Bottoms of Differing Shear Strength.

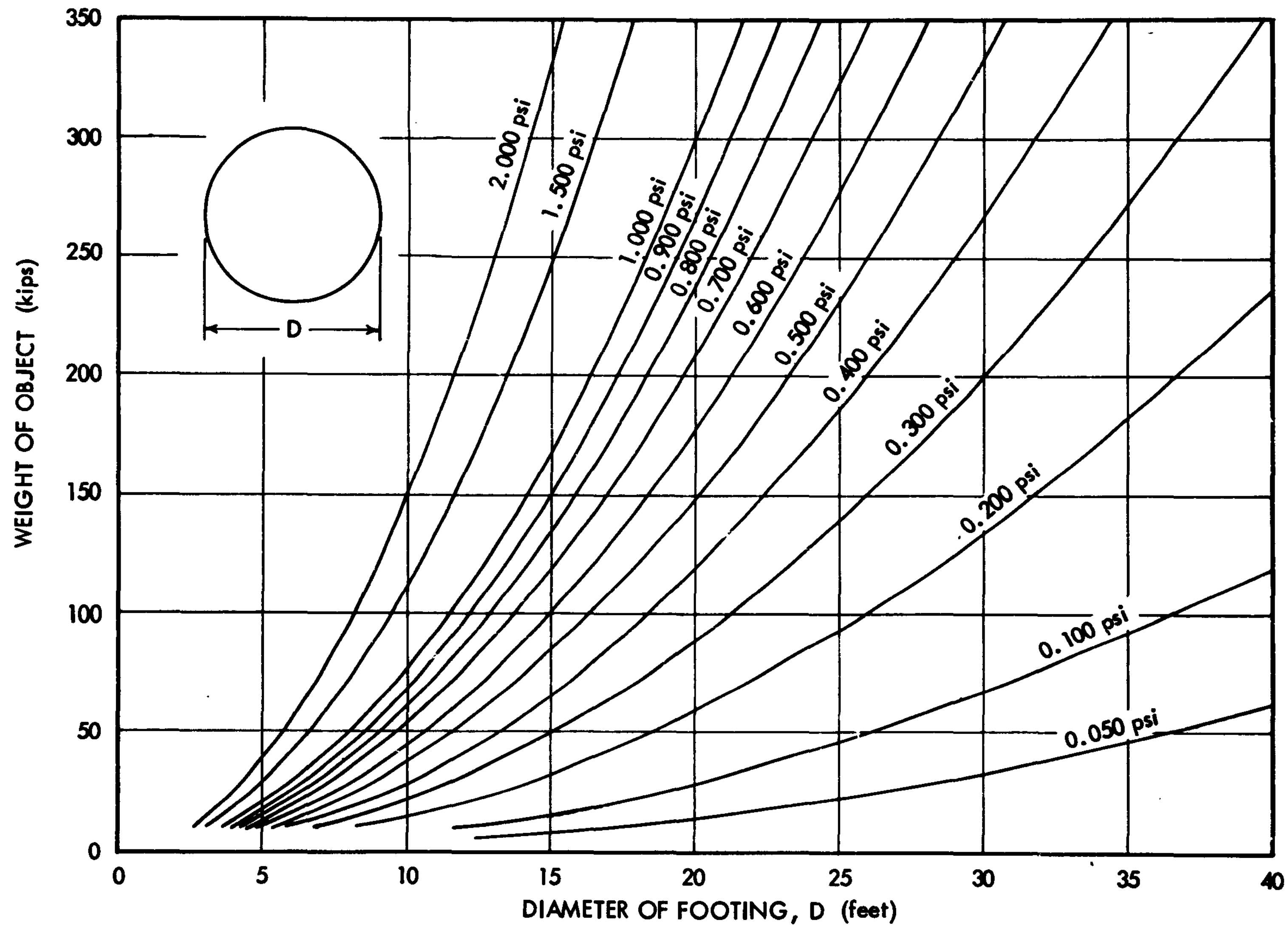

Figure 2. Plot of Diameter of Circular Footing Required to Support Reactors of Varying Weights on Bottoms of Differing Shear Strength.

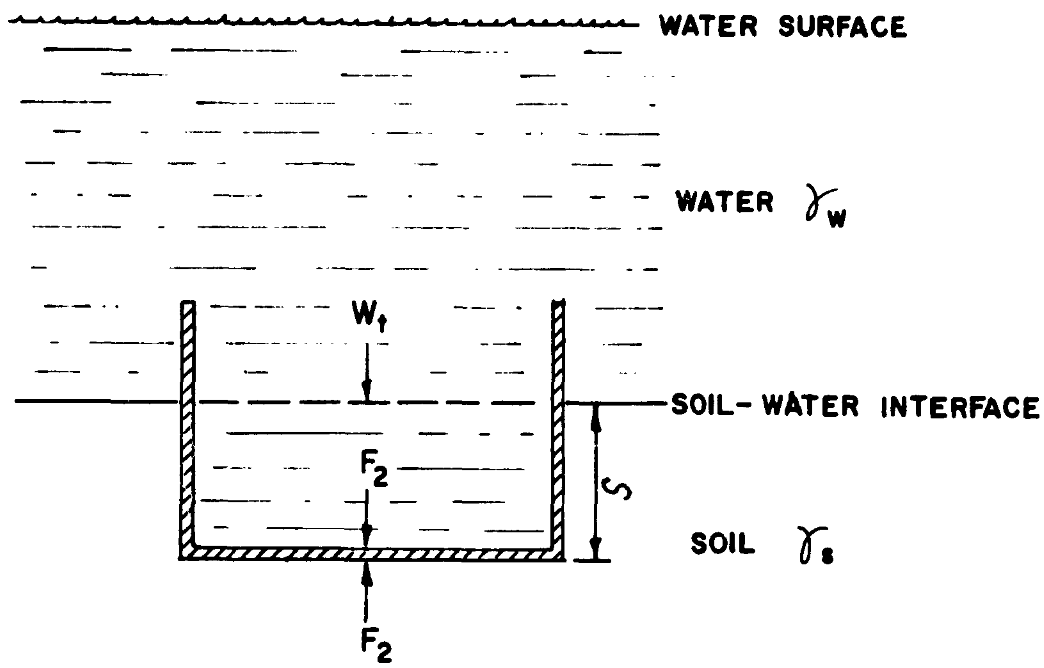

Figure 3. Diagram of Forces Acting on a Raft-Type Foundation Resting on a Viscous Liquid Bottom Soil.

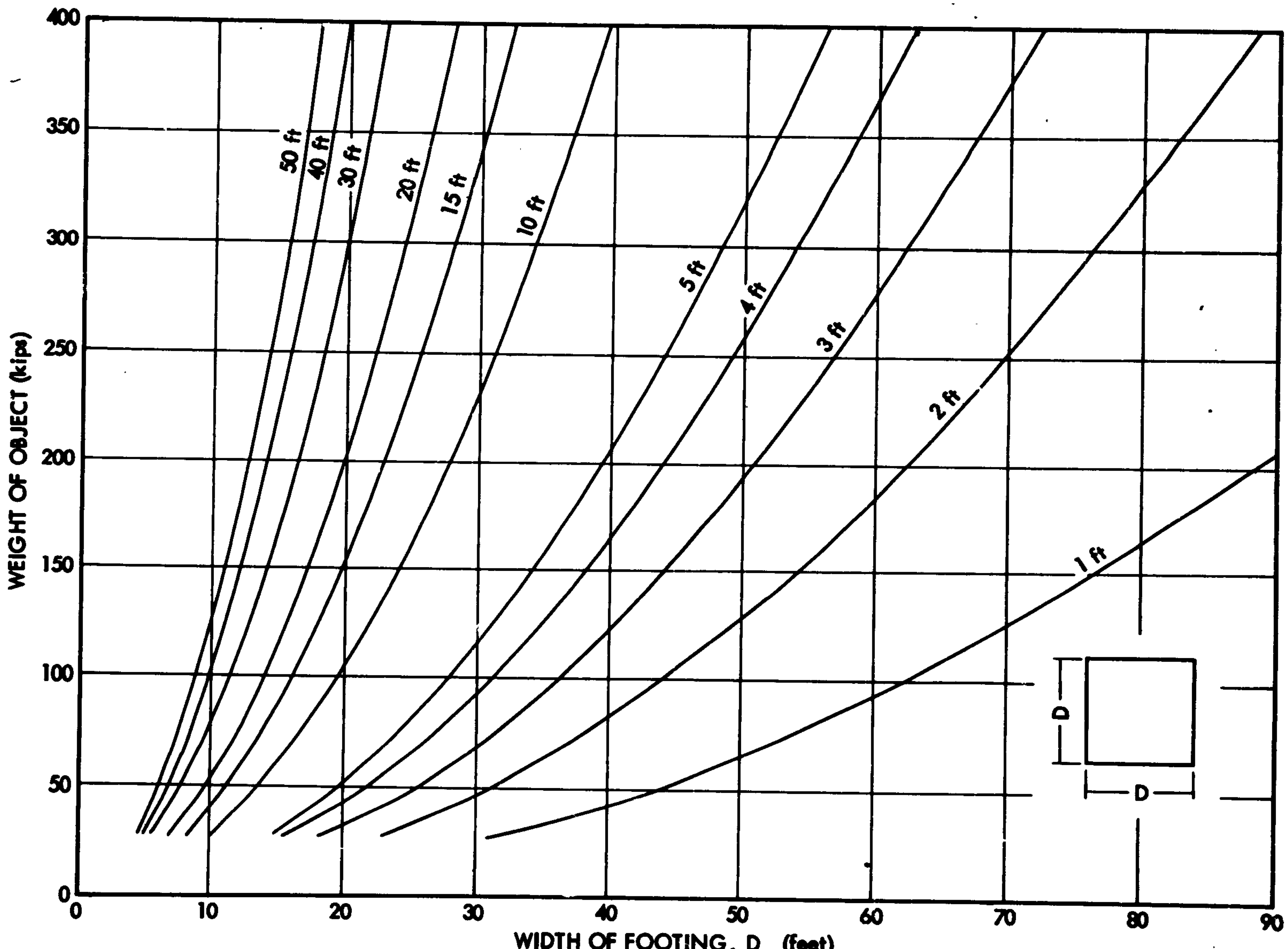

Figure 4. Settlement for a Square Footing Based on Buoyancy Considerations

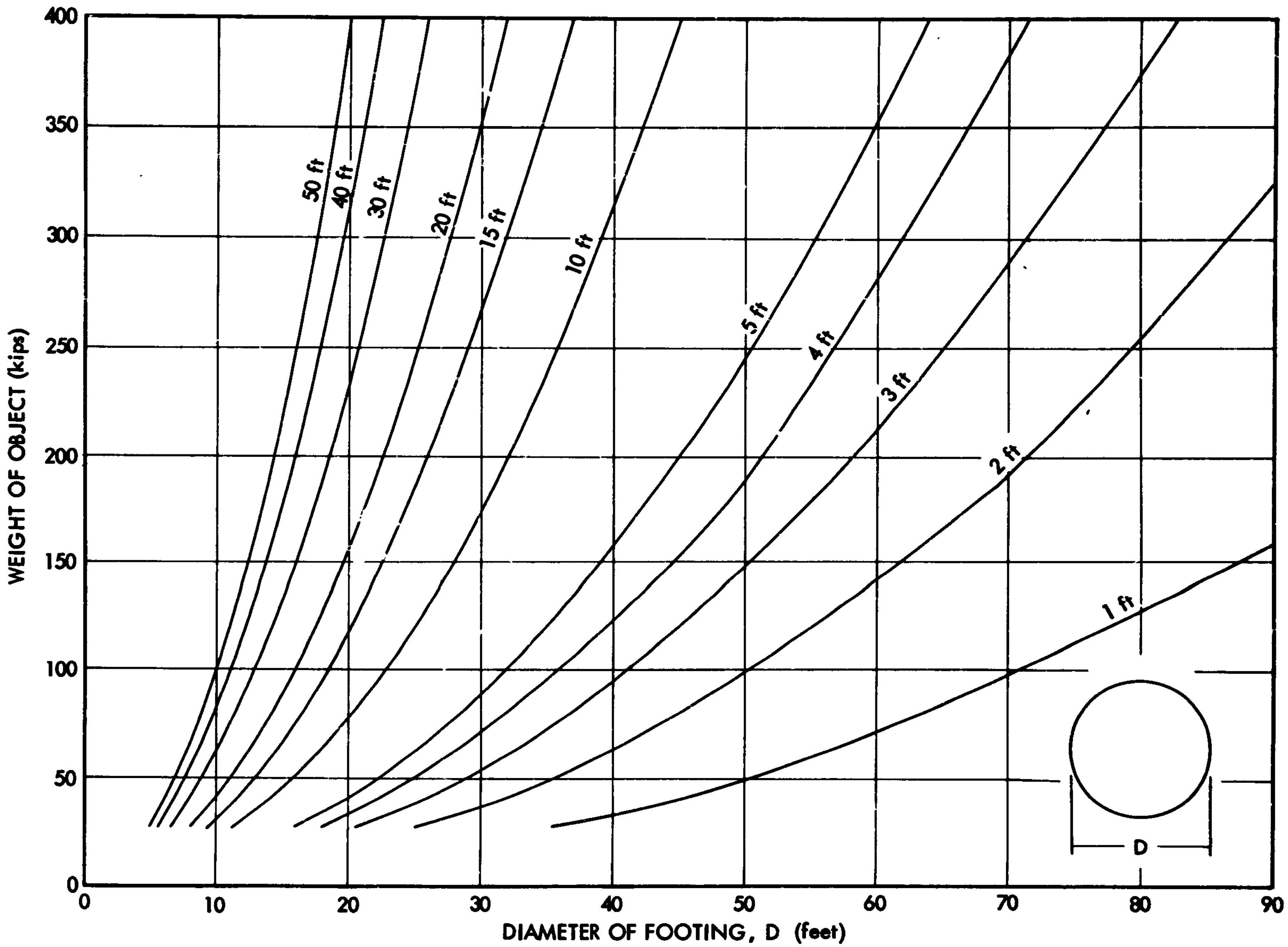

Figure 5. Settlement for a Circular Footing Based on Buoyancy Considerations

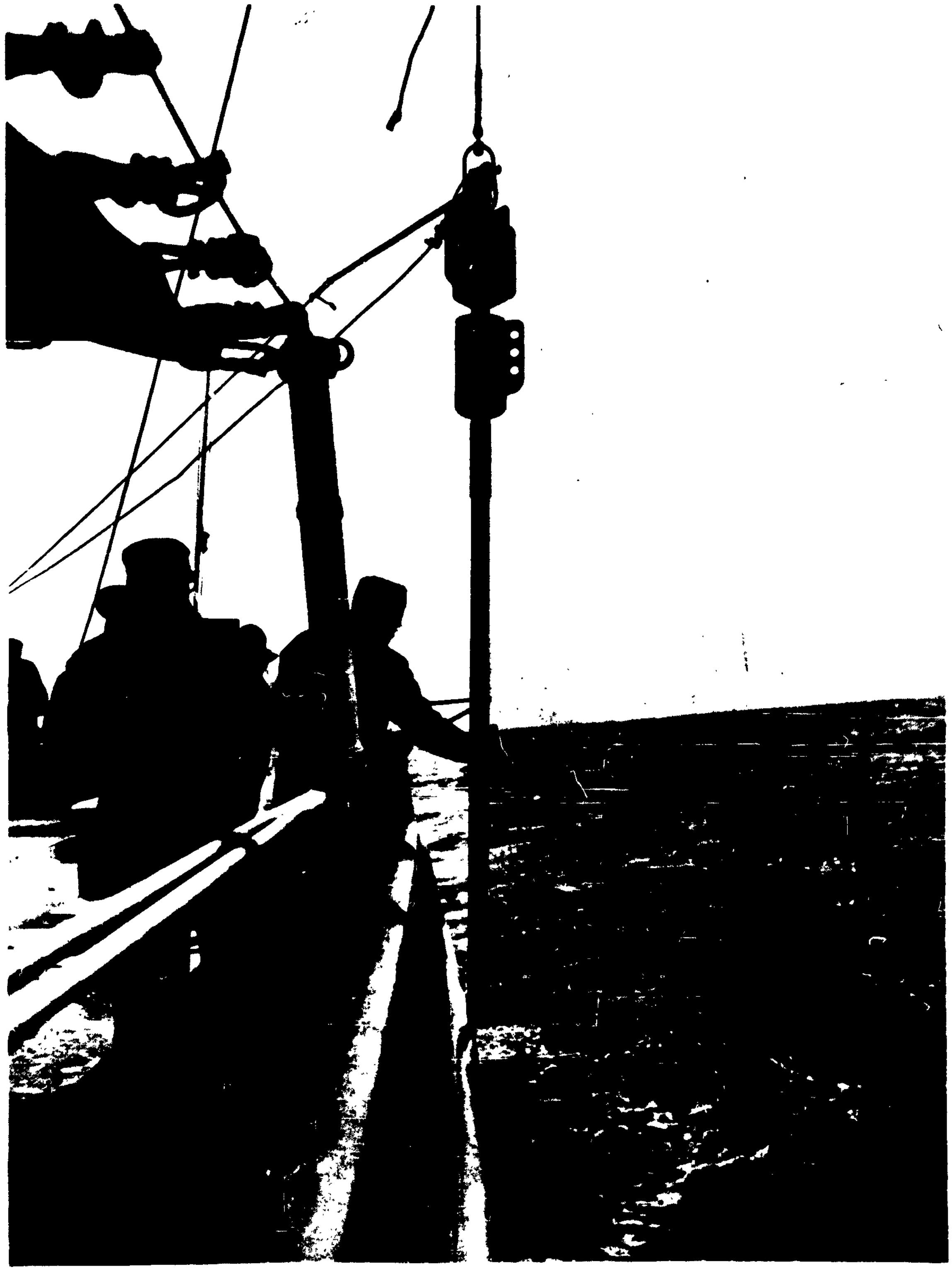

Figure 6. A gravity coring tool used to secure sea-floor soil samples for testing purposes.

CHAPTER V

DEEP OCEAN ANCHORAGE

P. A. Dantz

Introduction

One of the most difficult and least investigated aspects of a deep ocean installation is its anchorage. In current terminology, an anchorage is defined as a place for a ship to secure, using its own tackle and anchors, according to deKerchove, R (1948). In this paper, the term "deep ocean anchorage" is used to describe not only the site, but also the anchor and all the equipment necessary for anchoring a deep ocean installation. This broadened definition has been made since few deep ocean installations have been constructed, each presents a set of nearly unique conditions, and standard deep ocean anchorage practices are not firmly established.

Deep ocean bottom construction may involve suspending large, heavy, cumbersome loads by cable which may be three miles in length while maintaining, during a lengthy period, a vessel in a precise position and manipulating a device or system which may be 3000 fathoms removed, that cannot be seen, and may be working under an external pressure of about 8000 psi. Furthermore, many other factors from ship cranes, cable shock dissipators, connection hardware and anchors to the skill of the winch operator offer problems which are new and for the most part untried.

Ships and buoys, Isaacs, J. et al. (1963) have been moored at sea in deep water for weeks; holes have been drilled in the deep ocean floor, Long, E. J. (1962), Bascom, W. (1961), Horton, E. E. et. al. (1961), and trawlers have successfully grappled in the deepest ocean bottoms according to Hrorsley, M. S. and Stefson, H. C. (1946). However, fastening a structure to the deep ocean floor is a complex operation that can hardly be placed in the same class with the anchoring of an object which does not require footing support, the ability to withstand shock loads, and precision of position and orientation.

An important consideration concerning a deep ocean anchorage is the topography of the anchorage site. Land contours may vary from the extreme regularity of a salt flat to the steep inaccessible slopes of mountain ranges, and in much the same manner the ocean floor can be expected to offer a similar variety of topography. However, local irregularities nearly always exist but often cannot be detected from the surface. Also, the precision of an ocean bottom survey diminishes as depth increases. Hence, a desirably regular site cannot be assured and the anchorage system must incorporate a design to compensate for local topographic irregularities.

Another major consideration is the nature and composition of the ocean floor. See Chapter IV. Again, as on land, it may vary in hardness from exposed solid rock to a spongy consistency of highly fluid mud, and since for the greater depths an accurate analysis may not be known an anchor design will need to be capable of functioning under a wider range of soil conditions.

A third consideration is construction materials, as discussed by Gray, K. O. (1962), Muraoka, J. (1962), Muraoka, J. (1963). Since there is little available information on deep ocean corrosion, the life expectancy of an underwater system cannot be accurately predicted. However, existing materials can be used for large scale, short-lived construction with some assurance.

Established land construction methods may be extended, with modification and reservation, for use in the deep ocean. Due to the restrictive environment of the ocean, a considerable portion of the refinements of developed land construction practice must be abandoned and deep ocean anchorage systems must be capable of functioning under a much greater range of conditions.

Present Technology and Methods

Drilled-in-Piles and Foundation Types

Oil exploration and drilling by commercial enterprise accounts for a large percentage of the drilled-in-piles and hole-boring done today. Because actual capabilities developed and past experience gained is of significant monetary value to the individual companies, published or released data are meager, and often contradictory and quickly out of date. Consequently, information in this area is not necessarily reliable and should be used with reservation.

So far as is known, no attempt has been made to install a closely spaced collection of piles in depths of over a thousand feet. Cuss II is designed to drill in 18,000 feet of water and has already demonstrated its ability to drill in 12,000 foot depths. Shell Oil Company's "Trident," a surface platform, is claimed to be able to drill in 1,000 feet of water and has drilled successfully in 300 feet. The primary unusual drilling component of the "Trident" is a guide which rests on the ocean floor. It might be possible to modify this guide to drill and position a number of closely located piles, on which a deck could be prefabricated and lowered on the pile to provide a stable submerged platform. The "Trident" appears to be the most capable existing facility which can perform this task in depths up to 1000 feet.

Standard Drag Type Anchors and Systems

Standard drag type anchors do not lend themselves to deep ocean bottom installations because of the considerable horizontal distance needed to adequately set this type of anchor, according to Towne and Stalcup (1960). Since this anchor primarily offers horizontal resistance, even a group at 120° would not provide the desirable security since resistance to uplift is small. Large amounts of line and gear would render a deep water bottom installation impractical.

Dead-Weight Anchors

Dead-weight anchors have successfully been used for surface and subsurface buoys, as reported by Isaacs (1963). Although they may be used for long structures, the primary disadvantage with dead-weight anchors is the low weight-to-holding-power ratio. Also, hauling the necessarily large dead weights to sea is costly.

Explosive Anchors

Explosive anchors (embedment by explosive charge) have been developed and tested for use in shallow water. The basic construction of a typical explosive anchor should permit ready adaptation to deep ocean work, with the main problem at present the development of a neutral pressure propellent. This type of anchor has exhibited vertical holding power in the 100-150 kip range. A desirable feature is its consistent holding power under a wide range of soil conditions.

Future Developments

Current and near future deep ocean construction will be done mainly by prefabricated self-contained units lowered into position by a surface vessel. Any structural fabrication in deep water by direct or remote controlled means under the present technology is apparently not feasible. Small installation units will be hauled to the site and lowered into position. Larger units will be either towed to the site and sunk or assembled from prefabricated parts on or near the surface at the site and then lowered into position. The ocean floor presents many local irregularities which must be accounted for in the design of the anchorage system. Depending on the installation, local floor irregularities may be overcome by the use of movable arms or by adjusters at the extremities of a rigid system. Floor irregularity may also be overcome by floating the deep ocean installation using buoyant material and explosive, drilled, or stake pile anchors. The disadvantages of floating structures on the ocean floor are the possibilities of currents, fouling, loss of buoyancy, and anchor pull-out.

Soil bearing capacity for a bottom resting system can be obtained by the use of bearing plates at the unit's extremities. The entire unit can be secured to the floor by imbedding self-expanding anchors, thus rigidly fixing the installation in a firm position.

Orientation can be obtained with a universal cradle. The simplest method to obtain vertical orientation is by the use of weights, whereas azimuthal orientation would require a sophisticated system of power actuators and direction sending devices.

Placement of a deep water installation may be accomplished by lowering the unit to the bottom by cable, or by guiding it into position, untethered. The first method, discussed by Jones (1963), is within the capabilities of present day equipment, provided the unit does not exceed the weight and size capacity of available gear. The latter would require a guidance system similar to missile guidance systems, or other stabilization. Also necessary would be buoyancy control and sensitive propulsion equipment. This system, although free of the disadvantages of a tethered system, such as cable weight, dynamic loading from ship movement combined with cable stretch, and heavy winch requirements, would be more costly.

Current work in deep ocean anchorages is being conducted at the Naval Civil Engineering Laboratory, Port Hueneme. The conclusion of a state-of-art investigation has provided the basis for an anticipated testing program. As contemplated, testing of free fall deep ocean anchors will begin shortly and will be followed by deep ocean explosive anchor tests, bottom platform anchorage tests, deep ocean piling tests, and deep ocean anchorage systems. Considerable work has to be done in the field of deep ocean recovery before reliable systems become available.

A Possible Anchorage System

In considering the qualities of a number of different types of deep ocean floor anchorages for package units, preliminary investigation indicates that a type of anchorage system shown in Figure 7 offers good potential for success with minimum difficulty. Reliability, utilization of present technology, and flexibility were the basic governing design requisites. Reliability is maintained by use of a minimum of electronic and differential pressure devices. Also, where certain parts have an active role in the installation at the ocean floor, surplus components are provided to insure reliability. Operating depths of the anchorage appear to be unlimited provided adequate lowering equipment is available. The design can accommodate reasonable slopes and local topographic irregularities and may be used for soil conditions with reasonable bearing capacity where varying strata and consistency may exist.

In Figure 7 a universal cradle constitutes the main body of the structure. This affords a vertical orientation, self-oriented by weight. Supporting the main body are three rigidly attached arms, at the extremities of which are the bearing pads and anchors. The anchors are an explosive type and are drawn to optimum uplift bearing by submerged electric motors. Power might be supplied externally or by an internal, self-contained, short life service. Any number of bearing pad and anchor fingers could be used at the end of each arm. At least four as shown should be used to provide adequate bearing, anchoring and stability. The entire system except for the bearing pads is raised above the ocean floor to facilitate cooling water flow and minimize corrosion. Three point contact provides stability and gives latitude of design should lateral overturning forces be anticipated. The size of the bearing pads may be varied for different soil conditions. All components of mooring systems will be kept mechanical (except for the electric motors and firing system of anchors) to provide maximum reliability. All systems will be neutral pressure systems. The entire installation can be lowered by a single cable, with or without an electrical rider cable. Expendable buoyancy packs (not shown) may also be easily attached to aid in the lowering procedure. The basic design allows a range of carriage dimensions commensurate to package size.

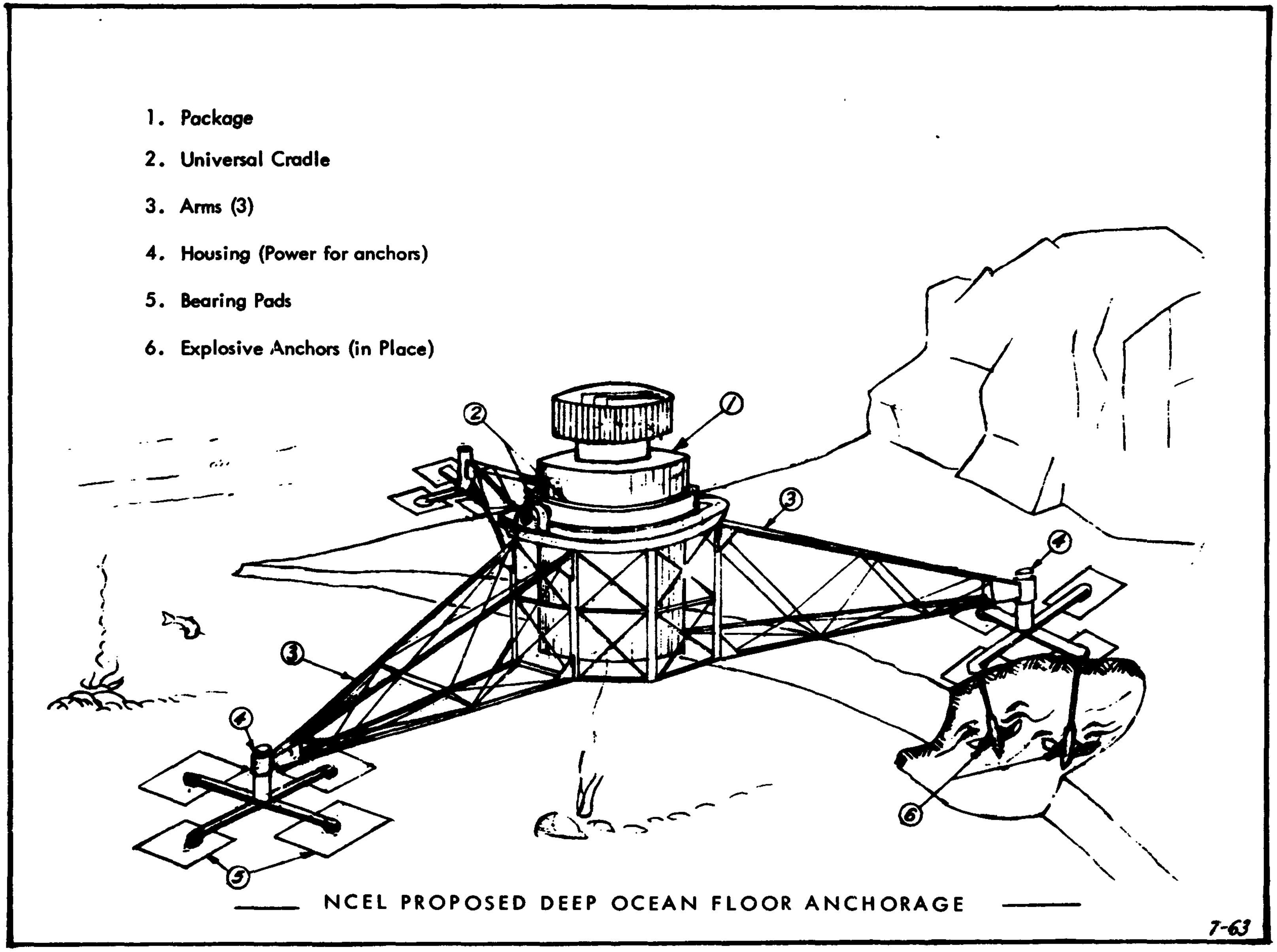

Figure 7. NCEL Proposed Deep Ocean Floor Anchorage

CHAPTER VI

MECHANICS OF PLACEMENT AND RECOVERY

B. Muga

Introduction

The objective of this chapter is to furnish information concerning a procedure for predicting the complete response to sea excitation of a moored construction-type barge. The response includes: (i) motion of the barge; (ii) tension induced in the lines used to raise and lower loads; and (iii) motion of the loads and the impact they experience on the bottom. Comments on the effects of currents are also included.

The wave-effect prediction utilizes excitation and frequency-response spectra together with probability theory. Therefore, response predictions are not made with certainty, but only in terms of the probability of their occurrence. A linear theory is used to predict barge response to regular waves. The result, termed a response operator, is applied to the sea spectra to obtain the response spectra.

Procedure

The prediction method is illustrated by applying it to the CUSS I, a moored barge used as a platform for an oil-well drilling rig, as shown in Figure 8. The wave-induced motion of this barge has been computed by Kaplan and Putz (1962). It is assumed that a load having a submerged weight of up to 1,000,000 pounds can be lowered through the 10-foot square center well of the CUSS I, and that such a load can also be lowered over the side by a boom.

It is assumed that construction operations are impractical in State 5 seas (McEwen and Lewis, 1953) or greater. This sea state is characterized by the formation of moderate to long waves, the growth of white foam crests, and the chance of some spray. The wind is described a fresh to strong breeze of approximately 22 knots. The statistical characteristics of the sea (Pierson, Neumann, and James, 1953) are presented in Table III, and the energy spectrum of the sea is shown in Figure 9.

Prediction of Barge Motion

The frequency-response spectrum of the time history of each motion of the barge as excited by the sea of State 5 is evaluated by the application of the appropriate directional ship-response operators, e.g., those in surge and heave. The operators are obtained from solutions of the equations of motion in regular sinusoidal waves (Kaplan and Putz, 1962), or from model tests. They are functions of the barge heading relative to the dominant wave direction. The frequency-response energy spectra is used to predict probably barge behavior, such as average or extreme values of the barge and mooring line tension amplitudes. Typical values for Sea State 5 are given in Figure 10.

Prediction of Wave-Induced Line Tensions and Impacts

Boom-lowered loads are more sensitive to the rotational motions of the barge than are center-well lowered loads, and they additionally require consideration of the boom azimuth angle. The minimum root-mean-square (rms) values of load displacements, added dynamic line tension, and vertical load acceleration for boom-lowered loads are presented by Kaplan and Putz.

Kaplan and Putz assumed that the vertical angle of the boom is constant at 60° from the horizontal, but it may be desired to change the boom angle to provide clearance of the load with the barge sides. The values denoted by asterisks in Table IV have been obtained with this modifying assumption, but they neglect phase relationship. The effect of this assumption is to increase the minimum rms values for load displacement in surge and sway.

Barge translatory motions (surge, sway and heave) are usually ignored, with little loss in accuracy.

A center-lowered load of 1,000,000 pounds from the CUSS I in a State 5 sea at a heading of 90° with the waves may be expected to induce added tension over a 4-hour period on the order of 148,000 pounds in the lowering lines, or about 15 percent additonal load. The maximum impact force on the bottom may also be expected to be a maximum of 148,000 pounds if the instant of impact is allowed to occur at random. The load can be placed within a circle of 18.2-foot diameter.

For a boom-lowered load of the same weight, the added tension in the lowering line increases to 305,000 pounds or approximately 30 per cent of the load being lowered. The accuracy in placing is much less for the boom-lowered load than for the center-lowered load.

Forces in the mooring lines, added tensions in the lowering lines, impact forces on the bottom, and displacements of the load for other barge headings and for other time durations may be predicted by application of the procedures presented by Kaplan and Putz.

Load Displacement Due to Currents

In lowering a load to depths of 6,000 feet of water, lateral ocean currents on the order of 1/2 knot can cause displacements of the lowering line and line loads far in excess of the wave-induced barge oscillations. The current drag on the lowering line is the principal cause of these displacements. Initially, the currents act on the object being lowered while it is traveling through various layers of water. When the load nears the bottom, any initial displacements will tend to be compensated for by the weight of the object. As the deep currents are likely to be slower than the surface currents, most of the displacement in this position will result from surface currents acting on the upper length of the lowering line.

The current environment of the deep ocean is uncertain and varies with time and place (see Chapter I). Deep currents are generally unrelated to surface currents and may be in the opposite direction. In addition, interfacial waves (or internal waves) occur which can impose load oscillations much greater than the wave-induced moored barge oscillations.

In the absence of currents, the inertia and drag resistance of the load and lowering line will cause the load to perform much smaller excursions around its mean position than will the end of the line suspended at the surface. The elasticity of the lowering line will also tend to absorb some of the vertical oscillations of the point of suspension.

Effects of Load Shape on the Motion

The shape and physical dimensions of the load will tend to dampen its vertical oscillation. The hydrodynamically most stable position of the load must be determined, and the load should be stably supported at three points. The shape and attachment should be such as to mininze lateral gliding and to maximize vertical damping. For example, a disk-shaped object will descend slowly but will glide from side to side. Alternatively, a special damping object of three disks intersecting at right angles to the lowering line can be provided between the load and the lowering line. The lowering line should be elastically supported on the barge, as, for example, by a stack of truck tires. Thus, the load will not be forced to oscillate by the vertical motion (heaving) of the barge.

Characteristics of the Site

An on-site current survey should be undertaken in each location where an actual load-lowering operation is contemplated to learn the probably current environment for the time of year of the scheduled operation.

On the basis of such information, calculations can be made to determine the likely load displacement under the influence of currents, etc. These calculations include drag forces on the object, mooring line forces, and catenary displacement of the mooring line. Suitable damping disks, the shape and mass of the line and load, the elasticity of the line and the nature of oscillations to be damped can also then be determined. No estimates of the actual magnitudes of such displacements can be given here, as they will vary widely, depending on the prevalent conditions. It is likely that the effects of currents will have a much greater importance on accuracy of load positioning than will the effects of wave-induced barge oscillation.

Impact during initial placement is difficult to avoid and the structure's legs should be made pliant enough to absorb impact loads on the order of twice the static load. For example, a suitably braced tripod such as given in Chapter V, Figure 7 of this report might be considered.

Recovery of the Load

A load similar to a nuclear reactor is considered. Since only the recovery of the reactor core itself would probably be required, the handling equipment can be substantially lighter and faster than that used for lowering the entire reactor and shield. In both the recovery and replacing of reactor components, guide lines or even guide pipes could be used to minimize the danger of fouling components against the fixed structure. The possible static effects from binding that might require a greatly increased initial pull during retraction of the reactor should be considered.

The task of recovering perhaps 1,000,000 pounds in one piece seems impractical because considerable embedment, distortion, and secondary impact is probable, and the induced loads would be excessive for available handling equipment.

Summary

A brief example of load handling with a construction-type barge, spread-moored in the deep ocean has been given.

Values of load-line displacement and bottom impact, as well as mooring and line forces have been given for a State 5, currentless sea.

The implications of currents, gliding, load shape, recovery, and replacement problems have also been briefly considered.

TABLE III. Statistical characteristics of Sea State 5* for a fully arisen sea**

Wind velocity, defined for "State 5 Sea"	22 knots
Minimum duration	12 hours
Minimum fetch	100 nautical miles
Average wave height	6.3 feet
Significant wave height (average of the highest 1/3)	10.0 feet
Average of the highest 1/10 waves	12.7 feet
Significant range of periods	3.4 - 12.2 seconds
Period of maximum energy of spectrum	8.9 seconds
Average period	6.3 seconds
Average wave length	134 feet

*As defined in Encycl. of Naut. Knowledge, McEwen and Lewis, Cornell Marit. Press, Cambridge, Md., 1953 p 483.

**Source: Pierson, Neumann and James (1953), H. O. Pub. No. 603 (Observing and forecasting ocean waves).

TABLE IV. Summary of significant motions and forces

Parameter	1 RMS σ	2 A1/3 Significant	3 A max. (1 hour)	4 A max. (4 hour)
Translational Movements:				
Surge, "x"	0.57^{ft}	1.14^{ft}	2.11^{ft}	2.34^{ft}
Sway, "y"	1.70^{ft}	3.40^{ft}	6.28^{ft}	6.98^{ft}
Heave, "z"	1.83^{ft}	3.63^{ft}	6.76^{ft}	7.50^{ft}
Rotational Movements:				
Roll, φ $0.90^{radians}$	5.15^{o}	10.30^{o}	19.10^{o}	21.10^{o}
Pitch, θ $0.024^{radians}$	1.37^{o}	2.74^{o}	5.07^{o}	5.62^{o}
Yaw, ψ $0.012^{radians}$	0.69^{o}	1.38^{o}	2.60^{o}	2.83^{o}
Force in Mooring Lines:				
F_1 2700^{lbs}	2.70^{kips}	5.40^{kips}	10.00^{kips}	11.10^{kips}
F_2 2500^{lbs}	2.50^{kips}	5.00^{kips}	9.25^{kips}	10.50^{kips}
F_3 2700^{lbs}	2.70^{kips}	5.40^{kips}	10.00^{kips}	11.10^{kips}
F_4 2500^{lbs}	2.50^{kips}	5.00^{kips}	9.25^{kips}	10.50^{kips}
For a Center Lowered Load				
Load Displacements:				
S_x	0.57^{ft}	1.14^{ft}	2.11^{ft}	2.34^{ft}
S_y	2.14^{ft}	4.28^{ft}	7.82^{ft}	8.76^{ft}
S_z	1.83^{ft}	3.63^{ft}	6.76^{ft}	7.50^{ft}
Unit Dynamic Line Tension: (1.16 lb/slug)				
T (Added tension in lowering line for 500^{T} Load)	36^{k}	72^{k}	134^{k}	148^{k}
Vertical Load Acceleration: (1.16 ft/sec^2)				
(Impact force on bottom for 500^{T} Load)	36^{k}	72^{k}	134^{k}	148^{k}
For a Boom-Lowered Load				
Load Displacement:				
$S_x, \gamma = 0^{o}, 180^{o}$	0.52^{ft} $2.3^{*\,ft}$	1.04^{ft} $4.6^{*\,ft}$	1.93^{ft} $8.5^{*\,ft}$	2.13^{ft} $9.5^{*\,ft}$

*See section on Prediction of Wave-Induced Line Tensions and Impacts.

TABLE IV. Summary of significant motions and forces (cont'd)

	1 RMS σ	2 A1/3 Significant	3 A max. (1 hour)	4 A max. (4 hour)
$S_y, \gamma = \pm 90^\circ, 180^\circ$*	1.70^{ft} $8.5^{*\ ft}$	3.40^{ft} $17.0^{*\ ft}$	6.30^{ft} $31.5^{*\ ft}$	6.96^{ft} $35.0^{*\ ft}$
$S_z, \gamma = -180^\circ$	3.90^{ft}	7.80^{ft}	14.45^{ft}	16.00^{ft}
<u>Unit Dynamic Line Tension:</u> (2.40 lb/slug)				
$\gamma = -180^\circ$ T (Added tension in lowering line for 500^T Load)	74.5^k	149.0^k	276.0^k	305.0^k
<u>Vertical Load Acceleration:</u> (2.40 lb/slug)				
$\gamma = -180^\circ$ (Impact force on bottom for 500^T Load)	74.5^k	149.0^k	276.0^k	305.0^k

NOTE: k = Kips

*See section on Prediction of Wave-Induced Line Tensions and Impacts.

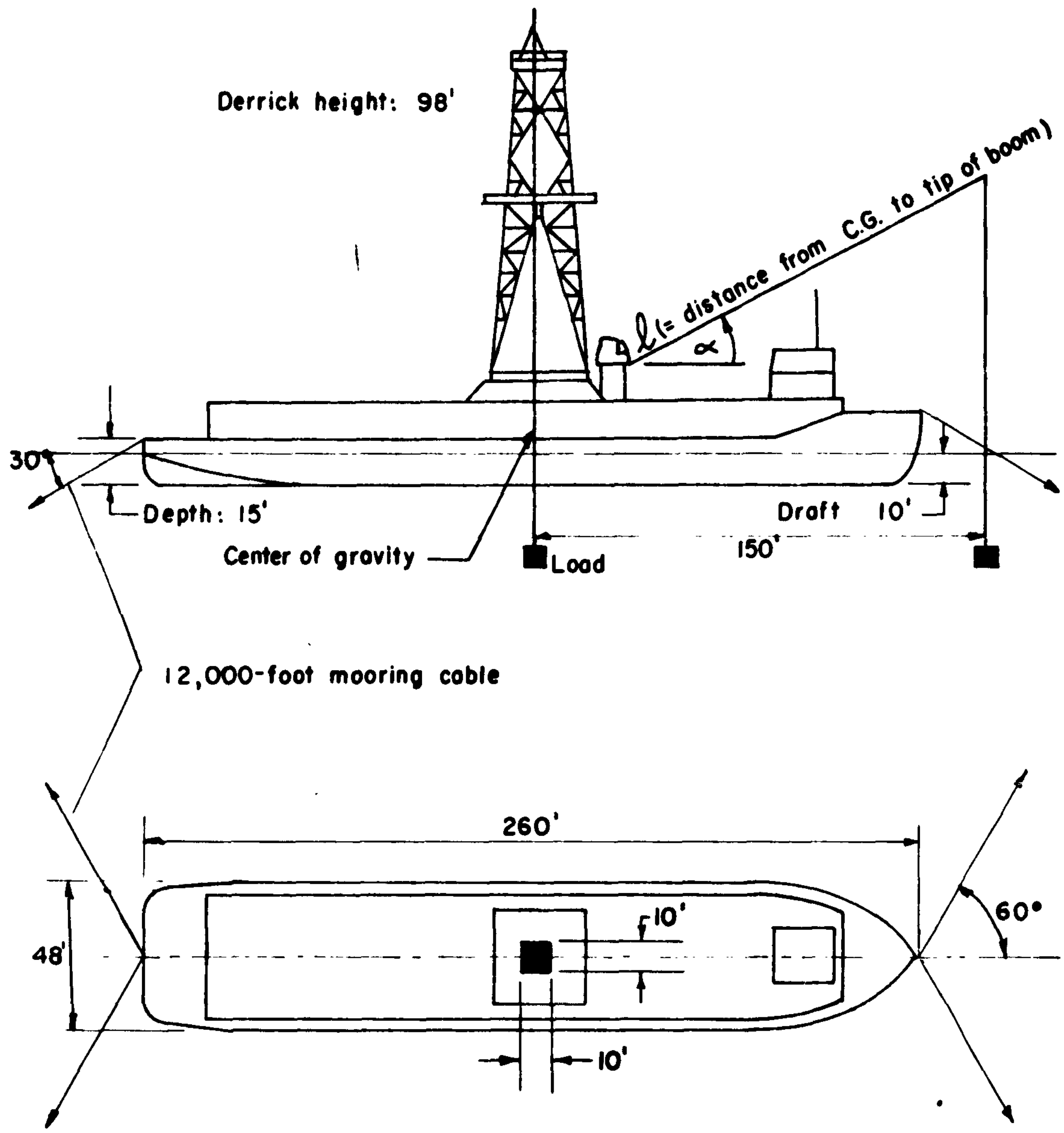

Figure 8

Schematic Diagram of Moored Barge
(Profile and plan views)
(from Kaplan and Putz, 1962)

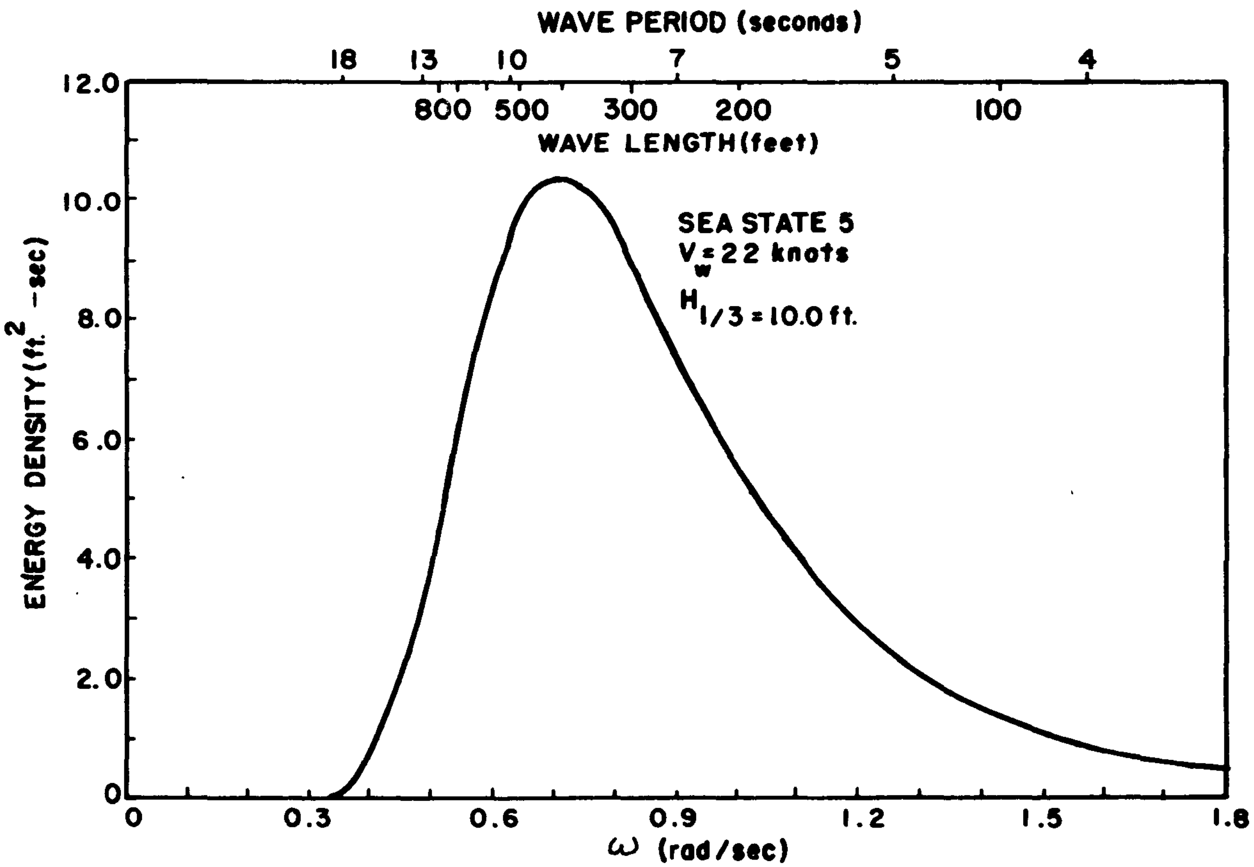

Figure 9.

Spectral Energy Density for Surface Elevations, as used in Computations
(Neumann Model for Wind Velocities Indicated)

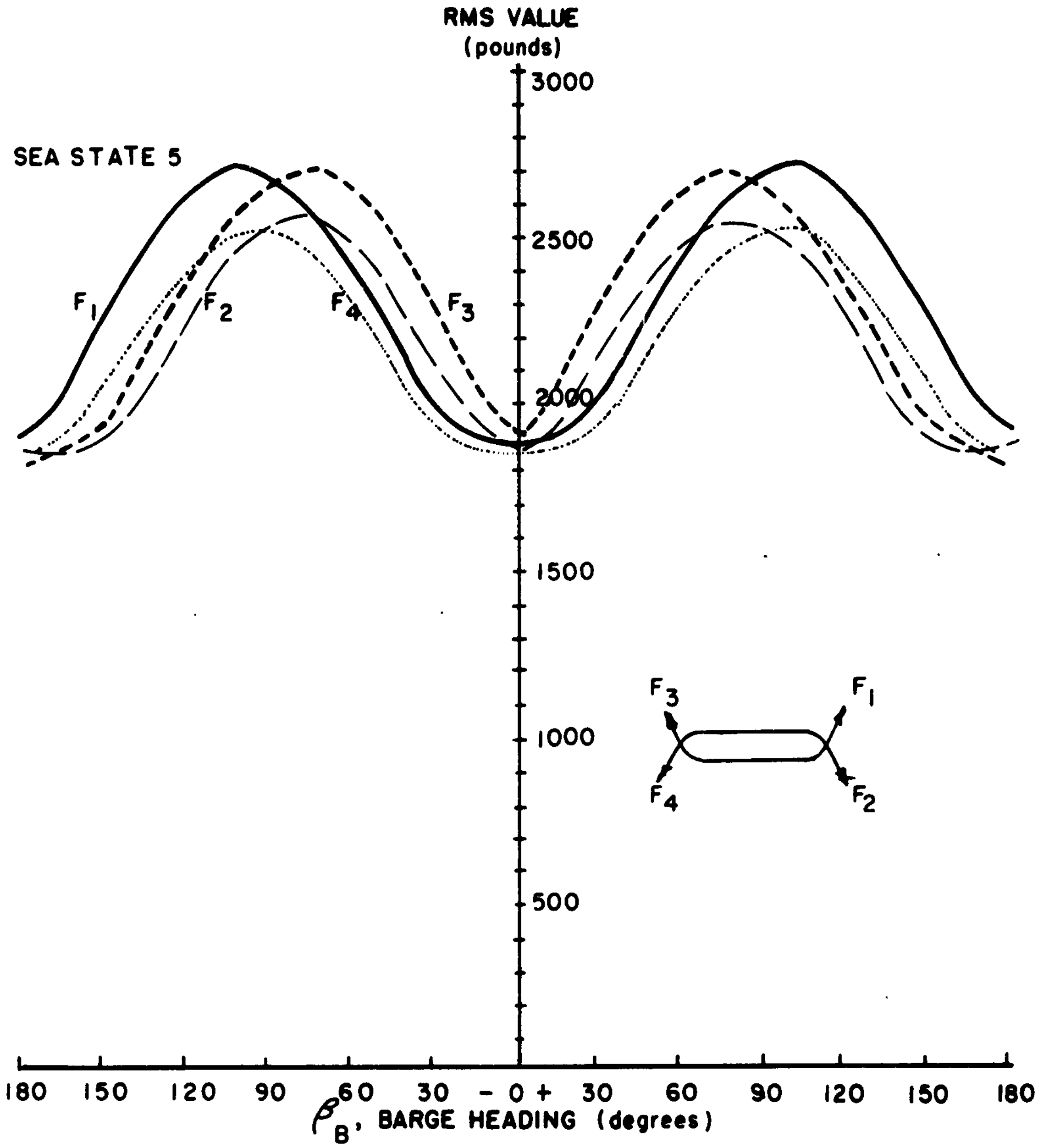

Figure 10.

RMS Values of Mooring Cable Forces as a Function of Barge Heading
at Sea State 5
(from Kaplan and Putz, 1962)

CHAPTER VII

UNDERWATER VISION AND TELEVISION

R. D. Hitchcock

For visual inspection during the installation and maintenance of a bottom-mounted deep-ocean nuclear reactor, it will be necessary to employ a closed-circuit television system, which is monitored at the surface. A secondary use of television would be in searching for the reactor in the event of loss of marker buoys or failure of bottom-located hydrophones.

Underwater Illumination

From the time of the earliest work in undersea television to the present no particular sophistication has been employed in artificial lighting schemes. From the beginning it has been realized that artificial light sources should be positioned in such a way so as to reduce veiling luminance to a minimum. Veiling luminance is produced by light scattered back into the camera lens as the result of suspended matter between the target and camera. Although pure water will cause a certain amount of light scattering, scattering of light in the ocean is predominantly due to transparent biological organisms and particles large compared with the wavelength of the light, Duntley (1963).

Some of the earliest undersea television work, Engleman (1948) was done during the Bikini atom-bomb tests in 1946 and artificial illumination was provided by two Navy diving lights, rated at 1000 watts each, attached to arms protruding from the camera housing. The length of each arm was about three feet, so that, for ranges within ten feet, not more than about half the total amount of water in the viewing field (24°) between camera and target could produce back scatter. Actually only two tests employed the artificial light sources; for most of the observations it was found that penetration of sunlight was sufficient to illuminate targets. Maximum observation depths were around 180 feet and maximum seeing range around thirty feet.

Studies, ONR London (1953) made by the Admiralty Research Laboratory in connection with the undersea television search and identification of the submarine, AFFRAY, lost in the English channel in 1951, have indicated that an unfiltered tungsten light source is as satisfactory as a mercury-discharge light. A British televison manufacturer, Pye, Ltd., developed a mercury discharge lamp at the time of the AFFRAY search, and an investigation by the Admiralty Laboratory showed that this type of lamp offered an improvement in range of 30 to 40% over that for tungsten light. It was concluded, however, that the 3° focused beam of the mercury lamp was the feature producing increased range rather than the more intense illumination.

Evaluation, Shumaker (1962) of the external lighting systems for the bathyscaph, Trieste, performed during the period from October 1959 through December 1961 by the U. S. Naval Electronics Laboratory, indicates that tungsten light sources for deep ocean illumination are probably superior to mercury-discharge lamps; originally the bathyscaph was equipped with mercury lights, but these proved to be unsatisfactory mainly because the lamps could not withstand sudden changes in temperature. Since the temperature in deep ocean is near the freezing point, the lamp casing was required to withstand a sudden transition from a low ambient to a high lamp temperature then back again to around freezing temperatures when turned off.

The Trieste used a combination of two types of tungsten lamps in dives in the vicinity of San Diego. Fairly good results, both visually and photographically, were obtained. No television observations were made. One type of lamp was manufactured by Edgerton, Germeshausen, and Grier, and utilized a pyrex casing in direct contact with the seawater. A 300-watt projection lamp was housed inside the pyrex casing. The other type of tungsten lamp was a General Electric 150-watt lamp using a mixture of iodine and argon gases for prolongation of filament life. This light was housed in an aluminum casing constructed at NEL; the window was made of plexiglass and protected from heat damage by a water barrier. The Edgerton lamp is still being manufactured and is advertised as withstanding depths to 36,000 feet. The NEL light source was tested at 16,000 psi (30,000 feet) and operated satisfactorily for 21 hours. It failed in one hour under a pressure of 20,000 psi (40,000 feet).

Although it might be thought that the high luminous efficiency (light output per unit power input) and the spectral character of the mercury lamp would make it more suitable for undersea observations than a tungsten lamp, practially all undersea televison work (1) has utilized tungsten light. Evidently the practical problems of high voltage supply and protection against temperature gradients cancel the advantages of mercury light.

Excessive sophistication of lighting schemes for underwater television has been avoided up to the present time probably either because of the lack of off-the-shelf hardware needed to provide light of a special character or because of preoccupation, on the part of the investigators, with more immediate problems, such as simply getting

Note (1)
Engleman (1948), ONR London (1953), Admiralty Res. Lab. (1952), Cross (1954), U. S. Navy Gun Fact (1959)

the television camera down into the water without damaging or losing it.

One type of light source, which is now within the state-of-the-art, Fischer (1961) and which might provide a visual range about one-and-one-half times[8] that of past television systems (25-40 feet), Engleman (1948), Adm. Res Lab (1952) is the high-intensity nanosecond air arc. This source could supply intense light pulses at a reasonable repetition rate which, through synchronized gating at the camera, could make possible a marked reduction in veiling luminance. That is, by proper gating at the camera, only target light would be registered; back scattered pulses would arrive either too late or too early to get into the camera.

Actually, an entire system utilizing a high-intensity pulsed air arc synchronized with a gated television camera is not presently available anywhere as a packaged shelf item. The air arc has been developed at the Air Force Cambridge Laboratories and has been tested for single-shot performance. Its inventor, Heinz Fischer, presumes that the source could deliver 1000 pulses/sec without appreciable erosion of the electrodes, Fischer (1961). Since the energy for a single pulse is around 10^{-2} joules, the amount of power needed to drive the arc at 1000 pps would be small. Although a nanosecond gated television camera is not presently available as a shelf item, an image orthicon camera could be gated in this manner by providing a simple electron chopper between photosurface and photoconductive target, Jenkins & Chippendale (1951).

In recent years there has been some talk about utilization of a laser for undersea illumination, Dulberger (1961), Weber (1963). While the power density (lumens per target surface) available from existing visible-light lasers is considerably higher than that from any other source, the laser light is confined to a needle beam--a feature highly advantageous in a communication system. This feature would, however, be a definite disadvantage is an undersea illumination system. Attaining a reasonable field of illumination and simultaneously preserving the high power density would require a high-speed scanning device--some kind of mechanism which would cause the laser beam to describe a spiral or saw-tooth raster. Furthermore, veiling luminance would still have to be eliminated in some way because, with the increased power density provided by the laser, back scattered light would be more pronounced than ever. Pulsing the laser and gating the camera would accomplish this in the same way as with the air arc. Another, equally complicated, method of back scatter reduction from a laser beam might be the use of a double pinhole aperture in front of the camera describing a raster in synchronism with the source, Dulberger (1961).

At the present time, then, it appears that tungsten lamps, of the order of a few hundred watts each, positioned on either side of the television camera as far to the side as practicable, will provide satisfactory artificial light at great depths in the ocean. At depths where sunlight penetrates sufficiently for illumination purposes, artificial lights can, of course, be dispensed with. This may be as much as 180 feet, according to a report, Engleman (1948) of the Bikini television work. Edgerton has recently come out with an incandescent lamp which consists of three 400-watt tungsten-iodide bulbs in a single high-pressure pyrex glass housing. The lamp is equipped with a reflector which can be manually adjusted to provide illumination cones between 10 and 60 degrees.

NCEL has recently let a contract for the construction of an undersea television and photographic system, in which tungsten-iodide lamps will be housed in a transparent casing (glass or quartz) which, in turn, will be encased in clear mineral oil contained in a metal housing supplied with a glass window. The transparent casing for the tungsten-iodide bulb is needed to prevent deposition of iodine crystals on the interior of the bulb; an air space between bulb and casing will prevent cooling of the bulb surface. The contract specifications require that these lamps withstand depths to 1000 feet; with suitable housings they should operate up to 30,000 feet as indicated by the Trieste work. The new Edgerton lamp is alleged to function satisfactorily at 40,000 feet with a lifetime of 50 hours at 1,200 watts.

Undersea Visibility and Television Detection of Submerged Objects

The range of an undersea visual detection system, i.e., the distance beyond which the target cannot be detected is a widely variable quantity and depends on a number of factors, such as positioning of illumination sources, sensitivity of the detector, amount of suspended matter in the water, and wavelength of the illumination. If the target provides its own light and no other light is present, detection is possible to distances of the order of 2,000 feet with a multiplier phototube photometer and conventional light source, Duntley (1963). This range is of the order of the maximum detectable penetration depth of sunlight, reported, Clarke & Wertheim (1956) to be around 2,000 feet.

Television systems, using an illumination source located near and moving with the camera, will in most cases not be able to identify small targets at distances beyond 40 feet, Engleman (1948), Admiralty Research Lab. (1952). One report, Admiralty Research Lab. (1952) describes an instance in which the ocean bottom was visible on the television monitor while 150 feet from the camera. In this case the water depth was 300 feet and no artificial lighting was used. Two main reasons for this exceptional television range were the extreme clarity of the water and the large size of the target (i.e., the ocean floor).

Because the sensitivity of the image orthicon television camera can be made considerably higher than that of the vidicon camera, most undersea television work has used the image orthicon. Both cameras utilize the scanning electron beam which describes a saw-tooth raster on a photoconductive storage target. The image orthicon*, however, employs an additional device ahead of the storage targets which gives this camera its higher sensitivity. This additional device includes a photoelectric surface; light from the objective lens produces photoelectrons from this surface which are accelerated onto the storage target. The sensitivity** of the vidicon camera, DeHaan (1958) is in the neighborhood of 10^{-5} lumen/cm, Engleman (1948) while that of an intensifier orthicon, Morton & Ruedy (1958) is better than 10^{-8} lumen/cm, Engleman (1948). As shown in Figure 11, it is possible to obtain a resolution of 320 lines at 10^{-8} lumen/cm, Engleman (1948) with the latter; yet, presumably, lower resolution would be tolerable for identification of certain types of stationary targets.

The attenuation of a beam of light by seawater results from both scattering and absorption, scattering being virtually independent of wave length throughout the visible region and absorption being markedly dependent on wave length, Duntley (1963). Since about 7% of the total scattering coefficient is the result of the presence of extremely fine particles and molecules the size of a wave length, it might be possible to reduce backscatter effects, and thus increase visual contrast, by employing red light in regions where there is an exceptionally low concentration of suspended particles (such as arctic waters). Seawater, however, possesses a single important window *** to electromagnetic radiation, the peak of which lies near 480 millimicrones (blue), except in coastal waters where dissolved yellow substances shift it toward the green. Figure 12 shows absorption versus wave length for Atlantic coastal water. It is probable that any reduction of scattered light, resulting from the use of red light, would be more than offset by the increase in absorption at wave lengths on either side of 480 mμ. Unfortunately, scattering data is not presently available for seawater at great depths; however, deep-sea photographic results indicate that, in general, deep-ocean water scatters light less than shallow water.

Because of the limited detection range of underwater television, its application to underwater search entails the use of an acoustic

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*Price range of image orthicon system: $30,000 - $50,000; price range of vidicon system: $5,000 - $10,000.

**The cone sensivity of the eye is around 10^{-5} lumen/cm, Engleman (1948) yet the rod sensitivity may be as high as 10^{-9} lumen/cm^2; however, it may take minutes to hours for the eye to adjust to optimum vision, Glasford (1955).

***Careful spectroscopic examination of seawater in the region 375 to 685 millimicrons, with a resolution of 0.02 mμ, has revealed no fine structure, i.e., no narrow-band window which might be advantageous in the event that a narrow band source, such as a laser, could be found.

detection system for initial location of the target, Cross (1954), Temple (1953). In location of the submarine, AFFRAY, a television system turned out to be indispensable since a large number of other sunken vessels were present on the English Channel bottom and the acoustic system could not differentiate one from another. The search, Temple (1953) for a sunken German submarine in 1953 in the coastal waters of the eastern United States relied on sonar for initial location of the target; but at a range less than 900 feet the sonar cone-of-silence made acoustic contact impossible. Within 900 feet of the submerged submarine the search vessel completed each target run by dead reckoning. Lowering of the television camera was not performed until the presence of the submarine under the surface vessel was confirmed by fathometer report. Depth of the water was about 120 feet.

An analysis, Hitchcock (1962) of some of the problems of using a pulsed-light television system for undersea search operations has been carried out at NCEL. This is an image orthicon system utilizing the technique of an internally gated camera synchronized with a high-intensity pulsed air arc, as already discussed above. An estimate of the seeing range of such a system, using attenuation and scattering data on California coastal waters, gives around 200 feet for submerged targets, such as sunken vessels, mines, and natural undersea objects. This is calculated to be about one and one-half times the range of this hypothetical system when the light source is continuous and the camera not gated. Although experimental data are used for the optical parameters of the water, this analysis presupposes such ideal conditions as the maximum possible air-arc light output and zero loss of signal between submerged camera and surface monitor. Also, the type of camera considered in this analysis is not representative of the cameras used in past undersea television work, but rather an intensifier orthicon, Morton & Ruedy (1958) which exhibits a sensitivity of the same order as that of a photomultiplier photometer. An estimate of the detection range of an ideal target, such as a 100% reflector with perfect retrodirectiveness, turns out to be around 300 feet.

Since there will always exist the possibility of failure of bottom-mounted acoustic signalers, a deep-ocean reactor should be provided with an illumination system of its own, which can be actuated accoustically from the surface. This would increase the seeing range of a television system by more than 50%; back scattered light would no longer be a problem and range would depend mainly on camera sensitivity and luminous output of the reactor lights. In the additional event of failure of these lights, the reactor should be covered with a highly reflective material with retrodirective devices attached at several points.

Transmission of Television Signals

In order to preserve picture quality in the transmission of television signals over long coaxial cables, it is in general necessary to install repeaters at regular intervals along the cable. In transcontinental television transmission it is necessary to design and maintain the repeaters to a very high degree of precision, and, in coaxial lines, repeaters are usually spaced about four miles apart. Any noise or distortion which occurs will be passed along to the other repeaters in the chain; because the effects are cumulative, each repeater must meet requirements which are considerably better than the overall requirements. Gains and equalization characteristics are frequently held to a hundredth of a decibel and, consequently, closed-circuit television repeaters are both expensive and complex.

In transmitting television information from great depths in the ocean to the surface -- distances of the order of 1 to 7 miles -- transmission cable should be as light as possible; and as much auxiliary electronic hardware should be kept off of the cable and camera rack as possible. This means that television observations of bottom-mounted deep-ocean structures will have to use the smallest-diameter coaxial cable for a given bandwidth requirement; and repeaters will have to be simple transistorized types which have diameters not too much larger than the cable diameter (so that it will be possible to winch the cable).

Such small-diameter transistorized line repeaters must be spaced at intervals of the order of a mile or less along a coaxial cable which is used to transmit signals with a few megacycles bandwidth. One study has been reported, Schimpf (1959) in which transistorized repeaters were spaced at 1/2-mile intervals along a 3/16" diameter coaxial cable; a one-mile experimental system was set up and it was determined that picture information could be transmitted with a 4.5 Mc bandwidth without noticeable degradation.

It will probably be possible to reduce the bandwidth requirements on transmission lines used for deep ocean television since observations will be conducted on stationary objects -- thus, permitting the use of slow scan television. The Naval Research Laboratory, Washington, D. C., is currently experimenting with a small, transistorized, slow-scan vidicon camera operating at one frame every two seconds, ONR (1963). Use of the slow scan may reduce bandwidth requirements from 4.5 Mc to around 60 KC. In laboratory experiments, good quality pictures have been transmitted over four miles of cable without insertion of repeaters. A disadvantage of slow-scan television is that it provides considerably less resolution than standard gandwidth television and, hence, would probably not permit detailed inspection of a bottom-mounted structure.

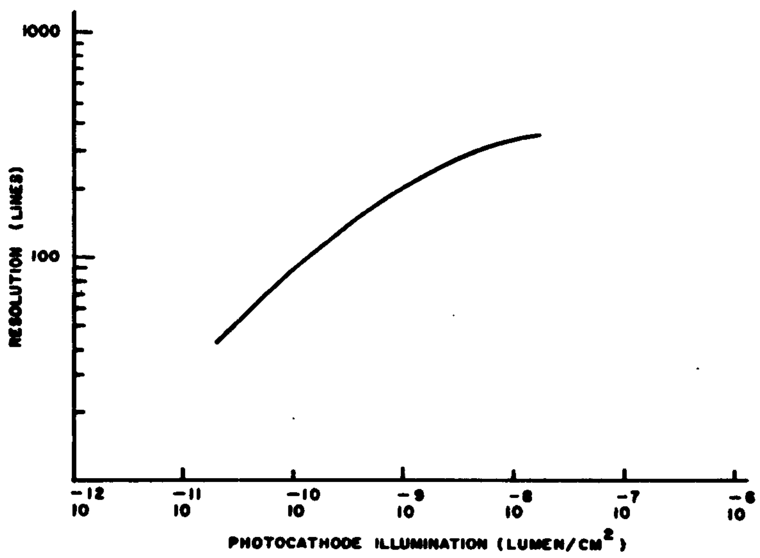

Figure 11. Resolution versus Photocathode Illumination for One-Stage Intensifier Orthicon

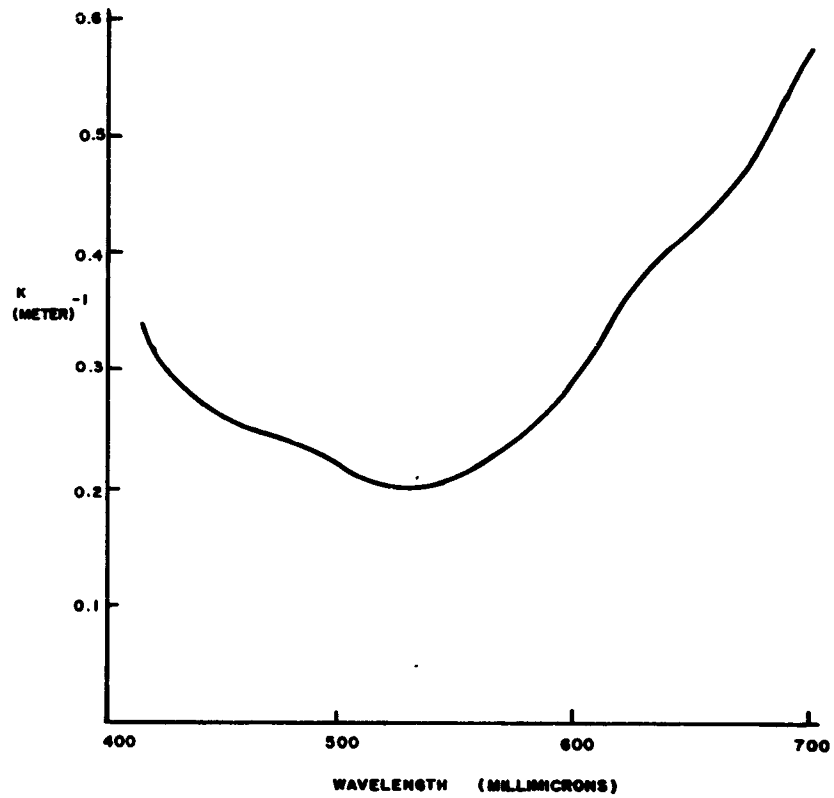

Figure 12. Seawater Total Absorption Coefficient, K, versus Wavelength for Atlantic Coastal Water (Huburt, 1945)

CHAPTER VIII

THE OCEAN AS A HEAT SINK

E. J. Beck

Warmed Water Circulation

While a moderate-sized reactor operating at low thermal efficiency rejects significant quantities of heat, it may normally have little effect on the deep ocean. A 2 MWE plant with thermoelectric conversion and operating at 3% thermal efficiency, heat to electricity, would reject about 2×10^8 Btu's per hour, and it is instructive to consider what the effects of this heat in the local water temperatures, etc., might be. Effects worth considering are the elevation of the water temperature, the probable extent of warm water's travel before diffusing to such an extent that the temperature elevation is trivial, possible elevation of temperature of water cooling the reactor, effects if any on marine life, and the probability of creation of a thermal convection cell which would evidence itself on the sea's surface. The latter might be important in that it would both allow approximate location of the reactor and easy detection.

The deep ocean's bottom water is characterized by being of fairly constant salinity and very low temperature; it is obviously polar in origin Sverdrup et. al., (1946), since from any other source on the ocean's surface the warming by the sun would produce temperatures well above those of the order of 2° to 3° C shown for deep waters in Figure 13, from Elmendorf and Heezen (1957).

The type of vertical circulation above a submerged nuclear reactor, occasioned by release of heat at the bottom, is not common in the ocean. Neither Revelle (1954)nor Sverdrup et. al. (1946) consider the possibility of significant upwelling over volcanoes, although the former shows a multitude of probable volcanoes in a plan of the northeastern Pacific, and does not preclude the possibility that some are active. Sverdrup mentions the possibility of thermal circulation from heat at depths but dismisses it as non-typical.

In the absence of known natural phenomena leading to active circulation from a submerged heat point source, it is desirable to cite or perform a scale experiment which will allow some deduction of the consequences of release of heat at depth in the ocean, and possibly infer the conditions under which, if ever, upwelling might be observed at the surface. A model study in the laboratory Taylor (1961) of a plume penetrating into a stable, stratified salt solution, gives considerable insight into the dispersion of warmed water in the ocean, particularly because the stratification was obtained in the experiment by differences in salinity similar to those which might occur in the ocean. As would be preducted, the less dense fluid, Figure 14, rises until a layer of similar density is encountered above the source, when it then spreads out. The vertical velocity eventually becomes zero. The simple model illustrated is not entirely typical of the deep ocean even if the ocean were in a fully stratified condition. In the ocean, the upward travel would be halted at a lower level than might be predicted from density considerations which control in the laboratory system for two reasons. First, the pressure change on an element of water rising from great depths is significant, so that the adiabadic decrease in temperature on expension would tend to decrease the density of the rising warm water column at a lower scaled level than would be observed in the scaled laboratory scheme. A level of equal density, the basic requirement for no continued upward buoyancy would be reached at a lower level. Second, ocean currents with horizontal velocity components would tend to accelerate the mixing of the relatively colder water outside the plume with the heated water in the plume, and a level of equal density would be reached at a lower elevation than would otherwise be predicted. The assumption of adiabadic expansion, that is expansion without heat transfer, while undoubtedly valid for a large system such as this, is in itself conservative, in that such heat transfer as occurs tends to lower the temperature of the plume, thus further halting upward convection from buoyant forces. Finally, if the heated plume from a deep ocean reactor should approach the surface, it would usually be completely quenched by the normal thermocline at about 1000 meters, Figure 15. Conceivably, a very large reactor in some waters might raise the water temperature at the ocean's surface.

Upwelling to the surface appears to be so highly improbable as to be an almost trivial consideration, but it is nevertheless useful to consider the probable volume of warmed water which might stand above the reactor under steady state conditions. Referring to Figures 14 and 16, we might assume as a worst case an apex angle of the heated cone of 30°; the usual dispersion by entrainment will normally be higher, as shown by the model, Figure 14. Further conservative assumptions are that at 3,000 feet over the bottom there is a horizontal current with a velocity of 1600 feet per hour (about 1/3mph). The effective diameter of the base of the inverted cone of heated water would be about 1600 feet, the volume of heated water about 2×10^9 cubic feet, the weight about 1.28×10^{11} pounds. The heated water coming of the reactor and rising would be appreciably above the average temperature, as it would be later cooled by dilution with the cool water entering the plume. It is therefore conservative for simplicity to assume that the entire 1.28×10^{11} pounds is uniformly heated by the 2×10^8 Btu's per hour rejected by the reactor. The average heating of the hypothetical plume would be about 1.5×10^{-3} °F/hr, scarcely enough to upset the equilibrium of the ocean.

Any heating creates upward drafts of water, and in a large rotating system like the earth, Coriolis effects produce rotational accelerations and complicated flow. An instructive but non-quanitative series of laboratory experiments is described by Fultz (1951). These lateral currents would further reduce the plume's temperature by assisting in its dispersal.

Faure (1961), Touloukian et. al. (1948), and Ostrach (1957) describe experimental work which may help make refined convection calculations for particular rates of heat rejection, etc., when the ocean conditions and reactor for a specific site are determined.

As may be deduced from Figures 14 and 16 and the references cited, in a large system such as the ocean, heating will not produce down-flow of warmed water, and the only portion of the water which will be appreciably affected is well above the ocean floor; no appreciable temperature rise at the reactor site may be expected.

The zone of warmed water may, of course, attract certain non-typical marine life, accelerate (or decelerate) corrosion, cause increase in fouling, etc. These last observations must be considered to be highly speculative until experimental observations may be made. Further, the insertion of large quantities of heat near the deep ocean bottom for protracted periods can probably only be done conveniently with an operating reactor or a very large dissipation of electrical power, so the crucial experiment will be difficult and expensive to conduct.

Heat Transfer Considerations

Whether or not the heated plume of rising water as described would upset the normal stratification of the ocean or cause upwelling on the surface, it is certain that the amounts of heat which might be released (of the order of 2×10^8 Btu's per hour) will usually be trivial in raising the temperature of the approaching water. The reactor will be continuously cooled by a copius and virtually unchanging supply of cold water, of the order of 2 to 8°C, Figure 13. Assuming that the reactor will not utilize active pumping to accelerate flow over the heat rejecting surfaces, the relationships describing the heat transfer by free convection are well known and simple in application: McAdams, (1958).

$$\frac{h_c L}{k} = 0.548 \left[\left(\frac{c_p \mu}{k}\right) \left(\frac{L^3 \rho^2 \beta g (\Delta t)}{\mu^2}\right) \right]^{\frac{1}{4}} \qquad (7)$$

Where h_c = useful coefficient of heat transfer

L = characteristic length, (height) vertical dimension of convector

c_p = specific heat

μ = viscosity

β = thermal coefficient of expansion

g = local acceleration of gravity

Δt = temperature difference, metal wal to bulk fluid

C = arbitrary constant in the dimensional equation

k = thermal conductivity

Equation (7), while formidable at first glance, can, for a particular situation, be readily reduced to a simple dimensional equation by solving for h_c, substituting average values to the physical properties at local conditions and by assigning a new arbitrary constant:

$$h_c = C \left(\frac{\Delta t}{L}\right)^{\frac{1}{4}} \quad (8)$$

For systems with L of 1' or over, it has been determined experimentally that its changing effect with height is negligible, further simplifying the equation to:

$$h_c = C\,(\Delta t)^{\frac{1}{4}} \quad (9)$$

From this relationship it can be seen that a final design must be a compromise wherein the cost of large, expensive surface areas in the convector is balanced against the disadvantage of higher low-side temperatures in the thermodynamic conversion cycle. To halve the effective temperature difference, convector surface to ocean, requires an increase of 2^4 or 16 times in the effective surface area for heat rejection. The use of relatively high surface temperatures, probably well over 100 F, will be encouraged by the adverse economics of providing large heat transfer surfaces at very high pressures.

From Chapters II and III it will be seen that temperatures above 125 F for the convector surfaces are desirable, as they will inhibit marine growth. Condenser surface temperatures of this order would produce undesirably high back pressures on a conventional turbine or reciprocating engine, inhibiting the achievement of high efficiencies. On the other hand, external pressurization by the ocean would simplify high side steam pressures near the critical pressure, which would improve efficiency.

In the aggregate, problems of constructing and operating unattended thermoelectric plants versus those of conventional thermal heat cycles appear about equally difficult but dissimilar Clark et al, (1960) and Rosenthal et al, (1960). The thermal cycle has the advantage in that it uses better established technology, while the thermoelectric enjoys the advantage of few or no moving parts, depending upon the designers' ability to accomplish nuclear control in the final design without active, moving mechanical parts.

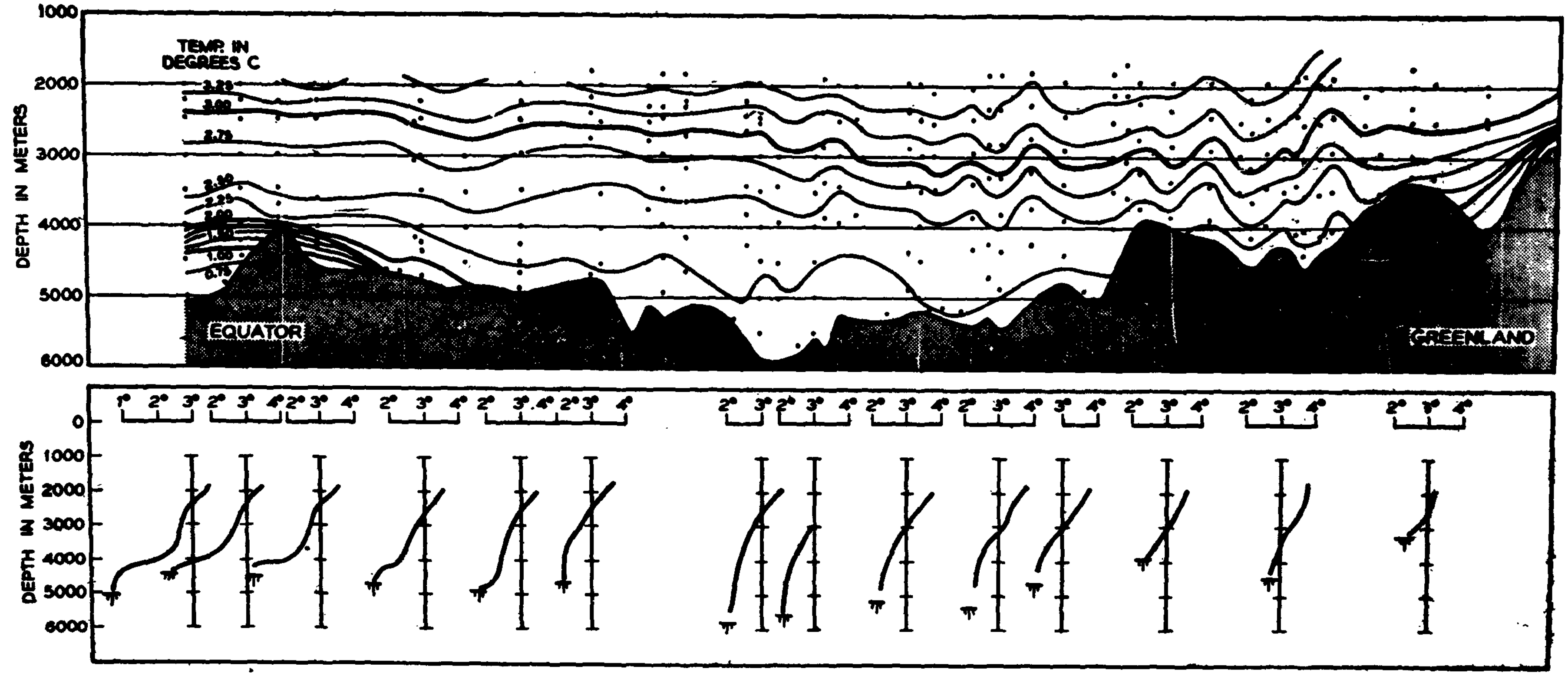

Figure 13. Profile 3, Equator to Greenland west of Mid-Atlantic Ridge. Top, isotherms in degrees Centigrade; bottom, gradients at corresponding locations. Data from 1920 to 1955. (Used by permission of American Telephone and Telegraph Company. From Elmendorf and Heezen 1957).

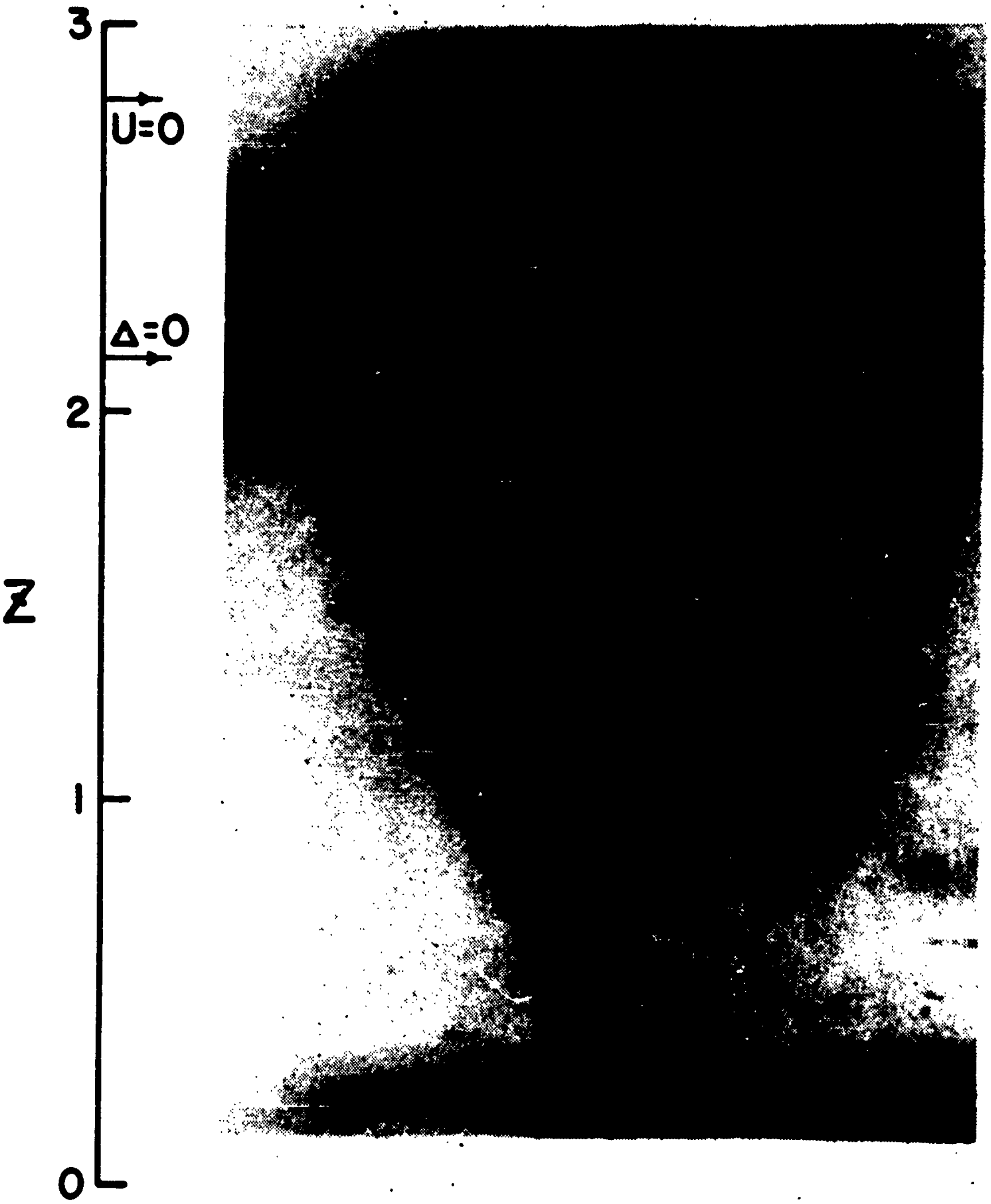

Figure 14. Maintained plume in a stably stratified fluid (methyl alcohol in salt solution). (Reprinted by permission of the Royal Society, London. From Taylor, 1961).

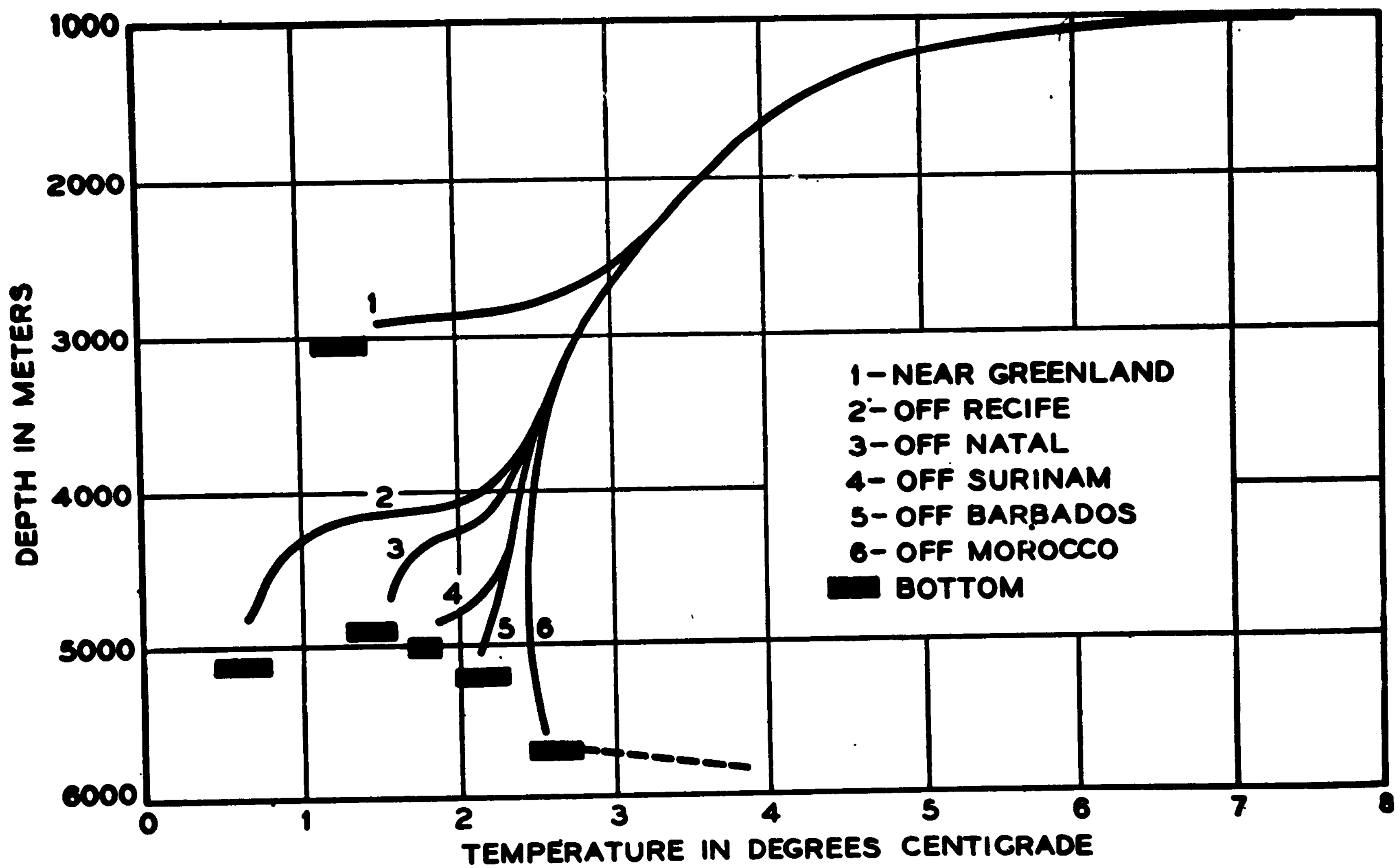

Figure 15. Deep-sea temperature gradients. Mean gradient in the sediments is indicated by the dashed line. (Used by permission American Telephone and Telegraph Company. From Elmendorf and Heezen 1957).

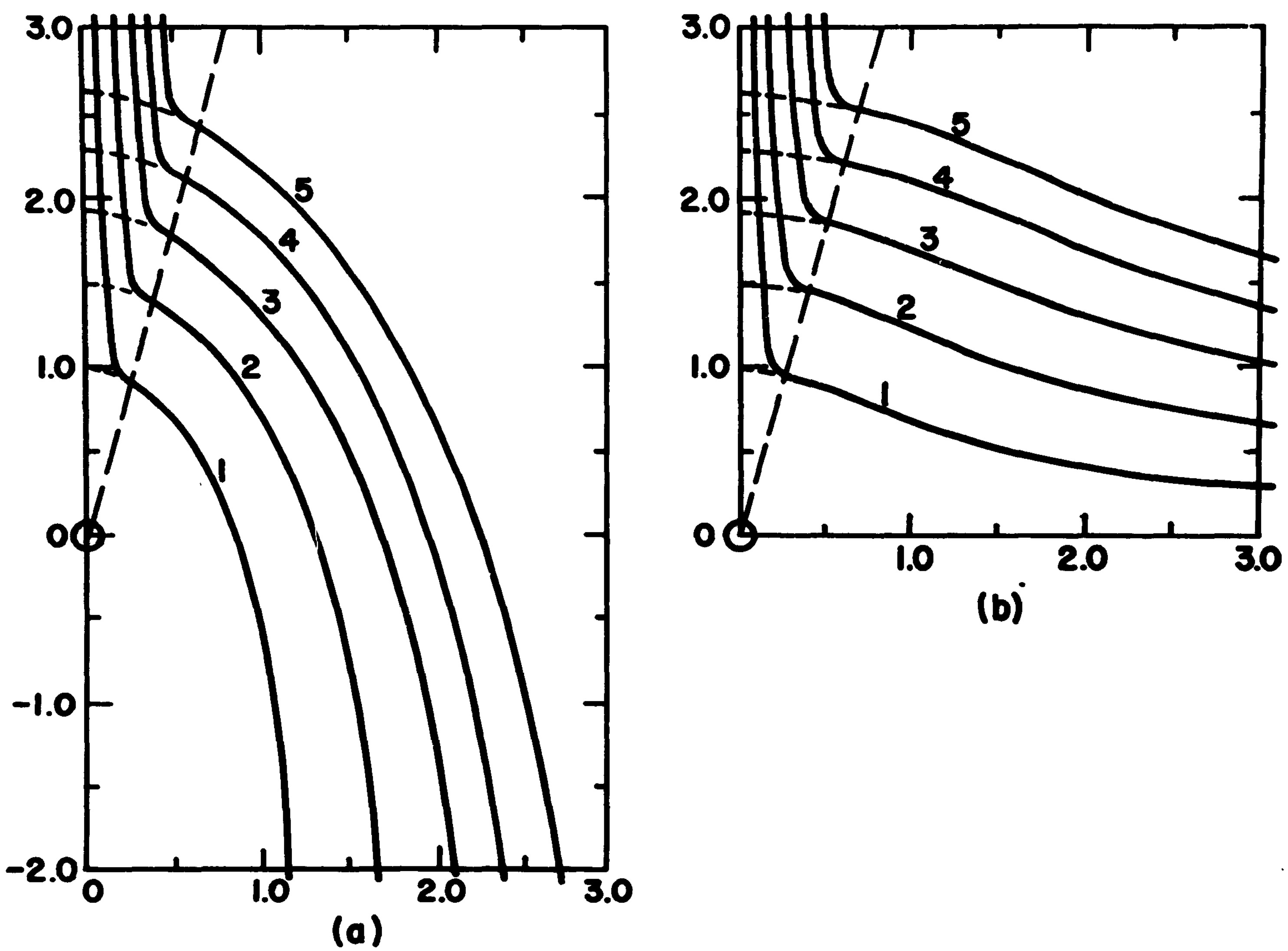

Figure 16. Stream lines of flow induced by a point source of heat. (a) Source unobstructed by ground. (b) Source at ground level. (From Taylor, 1961)

CHAPTER IX

RADIATION EFFECTS IN THE OCEAN ENVIRONMENT

F. W. Brown III

The Activation Problem

When a nuclear reactor is in operation, one has to know the effect of the reactor on the surrounding environment. Nuclear reactors designed for production of electrical power inherently produce as by-products excess heat and nuclear radiation. The former must be conducted out of the reactor, absorbed by the surroundings and removed from the vicinity. The nuclear radiations must be attenuated to the point where they are not harmful to the surrounding plants and animals. The elaborate shielding necessary to permit safe operation by human personnel of a conventional reactor is probably not needed for an undersea reactor, because of the shielding of the sea water and the absence of any human activity near the reactor while it is in operation. Nevertheless, shielding of the large neutron flux produced probably will be important because of the induced nuclear activity in the surrounding sea water. Any radioisotopes produced by the neutron flux will be in the sea water and can enter into the food chain of the oceanic ecology. Table V (Goldberg, A. (1963) lists the important elements found in sea water. The most abundant are hydrogen, oxygen, followed by chlorine, sodium, magnesium, sulphur, calcium, potassium, bromine, and others. To determine the importance of any radioisotope produced, as it relates to the marine environment, one must consider first the amount produced, the probable dilution in the sea water, the possible concentration by marine organisms (see Table VI), and its lifetime (half life, both physical and biological). Some of these quantities may be calculated for a particular size of reactor whereas others appear to be so extremely complicated that they are not susceptible to easy calculation and their overall importance can only be speculated upon.

Typical Example of Activation

We will assume that one has a reactor that is producing about 2 megawatts of electrical power by thermoelectric conversion of heat. At least 60 megawatts of thermal energy will be produced by such a reactor. The Army package power reactor (Rosen, S. S. (1958) is an example which produces about 2 megawatts thermal energy. If one scales this up to 60 megawatts thermal the neutron flux at the edge of the water reflector would be approximately the same as the example reactor that we are now considering. This flux of fast and thermal neutrons would be about 10^{14} neutrons/cm^2 sec. If this were unshielded, except for sea water, the average effective neutron flux Φ for activation of elements in the adjacent sea water would be about 8.7×10^{12} neutrons/cm^{2}sec. The reactor core is about 200 centimeters high and 100 centimeters in diameter. (The flux would occur at a distance of about 15 centimeters from the water reflector.) The volume of water subject to the effective average neutron flux $\bar{\Phi}$ would be about 10^6 cubic centimeters. In order to figure the probable activity generated in the sea water, one should consider the most abundant elements in the sea water and the ones with the largest cross section for neutron activation.

Sodium (Na^{23}), which is monoisotopic is one of the more abundant elements in sea water. When bombarded by neutrons the following reaction occurs, Na^{23} (n,γ) Na^{24}. The half-life ($T_{\frac{1}{2}}$) of Na^{24} is 15 hours. When the sodium has reached its saturation activity at a time $t >> T_{1/2}$ then the number of atoms of Na^{24} decaying per second is equal to the number of atoms being produced per second in the sea water.

The activity A_i of the ith isotope of any element present is given by:

$$A_i = \frac{\bar{\Phi}\, \sigma_i\, a_i\, c_i (.603)\ \ V\,(1 - e^{-\lambda t})}{W_i} \text{ disintegrations/sec} \qquad (10)$$

A_i = number of atoms of the ith isotope decaying/sec.

$\bar{\Phi}$ = effective neutron flux in neutrons/cm^2, sec.

σ_i = nuclear cross section for production of ith osotope in barns (10^{-24}cm). A complete listing of thermal neutron cross sections from Goldman, D. T. and Stetson, J. R. (1961).

a_i = isotopic abundance of the ith element as a decimal.

c_i = concentration of the ith element as a decimal.

.603 = constant, Avogadro's No $\times 10^{-24}$.

V = volume of water over which $\bar{\Phi}$ is effective in cm^3.

e = 2.718.

λ = decay constant = $\frac{.693}{T_{1/2}}$ in sec^{-1}.

$T_{1/2}$ = half life in seconds.

W_i = atomic weight of the ith isotope.

In the case of Sodium Na^{23}, substituting the numerical values in equation (10) gives:

$$A_{Na}{}^{24} = \frac{8.7.10^{12}\ (.505)\ (1)\ (1.06.10^{-2})\ (.603)(10^{6})}{23}\ (1 - e^{-\lambda t})$$

the term $(1 - e^{-\lambda t}) \cong 1$ if t $T_{1/2}$

so

$$A_{Na}{}^{24} \cong 1.22.10^{15} \text{ disintegrations/sec}$$

$$\cong \frac{1.22.10^{15}}{3.7.10^{10}} = 3.3.10^{4} \text{ curies}$$

This example assumes that all the water activated by passing near the reactor is not diluted; however, if the water were diluted in a cubic kilometer of sea water, the concentration would be only $3.3.10^{-5}$ μc/cc of Na^{24}.

Considering another abundant element, chlorine, under neutron bombardment Cl^{36} is produced by the following reaction Cl^{35} (n,γ) Cl^{36}. The half life ($T_{1/2}$) of Cl^{36} is 3.10^{5} years. For a very long half life compared to the irradiation time, equation (10) simplifies to:

$$A_i \cong \frac{\Phi\ \sigma_i\ a_i\ c_i\ \ (.603)\ V\ (\lambda t)}{W_i} \cong \frac{\Phi\ \sigma_i\ a_i\ c_i\ \ (.603)\ V}{W_i}\ \frac{(.693t)}{T_{1/2}} \quad (11)$$

substituting in the numerical values for the Cl^{34} (n,γ) Cl^{35} reaction we have:

$$A_{Cl}{}^{36} = \frac{8.7.10^{12}(31.6)(.7)(1.9.10^{-2})(.603).10^{6}(.693)}{35(3.10^{5})} \cong 1.5.10^{11}$$

disintegrations/sec for t = 1 year.

$$A_{Cl}{}^{35} \cong \frac{1.5.10^{11}}{3.710^{10}} = 3.9 \text{ curies produced/year.}$$

If this were diluted in one km^3 of sea water, the concentration would be $3.9.10^{-9}$ $\mu c/cm^3$.

Element	Abundance, mg/l.	Principal species	Residence time, years
H	108,000	H_2O	
He	0.000005	He (g)	
Li	0.17	Li^+	2.0×10^7
Be	0.0000006		1.5×10^2
B	4.6	$B(OH)_3$; $B(OH)_2O^-$	
C	28	HCO_3^-; H_2CO_3; CO_3^{2-}; organic compounds	
N	0.5	NO_3^-; NO_2^-; NH_4^+; N_2 (g); organic compounds	
O	857,000	H_2O; O_2 (g); SO_4^{2-} and other anions	
F	1.3	F^-	
Ne	0.0001	Ne (g)	
Na	10,500	Na^+	2.6×10^8
Mg	1350	Mg^{2+}; $MgSO_4$	4.5×10^7
Al	0.01		1.0×10^2
Si	3	$Si(OH)_4$; $Si(OH)_3O^-$	8.0×10^3
P	0.07	HPO_4^{2-}; $H_2PO_4^-$; PO_4^{3-}; H_3PO_4	
S	885	SO_4^{2-}	
Cl	19,000	Cl^-	
A	0.6	A (g)	
K	380	K^+	1.1×10^7
Ca	400	Ca^{2+}; $CaSO_4$	8.0×10^6
Sc	0.00004		5.6×10^3
Ti	0.001		1.6×10^2
V	0.002	$VO_2(OH)_3^{2-}$	1.0×10^4
Cr	0.00005		3.5×10^2
Mn	0.002	Mn^{2+}; $MnSO_4$	1.4×10^3
Fe	0.01	$Fe(OH)_3$ (s)	1.4×10^2
Co	0.0005	Co^{2+}; $CoSO_4$	1.8×10^4
Ni	0.002	Ni^{2+}; $NiSO_4$	1.8×10^4
Cu	0.003	Cu^{2+}; $CuSO_4$	5.0×10^4
Zn	0.01	Zn^{2+}; $ZnSO_4$	1.8×10^5
Ga	0.00003		1.4×10^3
Ge	0.00007	$Ge(OH)_4$; $Ge(OH)_3O^-$	7.0×10^3
As	0.003	$HAsO_4^{2-}$; $H_2AsO_4^-$; H_3AsO_4; H_3AsO_3	
Se	0.004	SeO_4^{2-}	
Br	65	Br^-	
Kr	0.0003	Kr (g)	
Rb	0.12	Rb^+	2.7×10^5
Sr	8	Sr^{2+}; $SrSO_4$	1.9×10^7
Y	0.0003		7.5×10^3
Zr			
Nb	0.00001		3.0×10^2
Mo	0.01	MoO_4^{2-}	5.0×10^5
Tc			
Ru			

Table V. Geochemical parameters of sea-water (From Goldberg, 1963)

Element	Abundance, mg/l.	Principal species	Residence time, years
Rh			
Pd			
Ag	0.0003	$AgCl_2^-$; $AgCl_3^{2-}$	2.1×10^6
Cd	0.00011	Cd^{2+}; $CdSO_4$	5.0×10^5
In	< 0.02		
Sn	0.003		5.0×10^5
Sb	0.0005		3.5×10^5
Te			
I	0.06	IO_3^-; I^-	
Xe	0.0001	Xe (g)	
Cs	0.0005	Cs^+	4.0×10^4
Ba	0.03	Ba^{2+}; $BaSO_4$	8.4×10^4
La	0.0003		1.1×10^4
Ce	0.0004		6.1×10^3
Pr			
Nd			
Pm			
Sm			
Eu			
Gd			
Tb			
Dy			
Ho			
Er			
Tm			
Yb			
Lu			
Hf			
Ta			
W	0.0001	WO_4^{2-}	1.0×10^3
Re			
Os			
Ir			
Pt			
Au	0.000004	$AuCl_4^-$	5.6×10^5
Hg	0.00003	$HgCl_3^-$; $HgCl_4^{2-}$	4.2×10^4
Tl	< 0.00001	Tl^+	
Pb	0.00003	Pb^{2+}; $PbSO_4$	2.0×10^3
Bi	0.00002		4.5×10^5
Po			
At			
Rn	0.6×10^{-15}	Rn (g)	
Fr			
Ra	1.0×10^{-10}	Ra^{2+}; $RaSO_4$	
Ac			
Th	0.00005		3.5×10^2
Pa	2.0×10^{-9}		
U	0.003	$UO_2(CO_3)_3^{4-}$	5.0×10^5

Table V. Geochemical parameters of sea-water (From Goldberg, 1963). (cont.)

Element	*Calanus* (Copepod) Vinogradov, 1938	Fish[a] (Average)	*Archidoris britannica* (Nudibranch) McCance & Masters, 1937–38	Sea water	Concentration factors		
					Copepod	Fish	Nudibranch
Cl	194	...	180	180	1.1	...	1.0
Na	100	100	100	100	1.0	1.0	1.0
Mg	5.6	36	156	12.1	0.46	3.0	12.9
S	25.9	259	7.1	8.4	3.1	31	0.85
Ca	7.4	52	262	3.8	1.9	13.7	69
K	53.7	383	20	3.6	15	109	5.5
Br	1.7	...	...	0.6	...	...	3
C	1113	ca 4100	ca 480	0.26	4,300	15,800	1,850
Sr	...	...	11	0.12	...	...	92
Si	1.3	...	...	0.001[b]	[illegible],000	...	...
F	...	...	69	0.01	...	...	6,900
N	280	1276	107	0.001[b]	280,000	1,276,000	107,000
P	24.1	256	6	0.0001[b]	241,000	2,560,000	60,000
I	0.04	...	...	0.0005	80	...	...
Fe	1.3	1.3	0.23	0.0002[c]	6,000	6,000	1,000
Mn	...	0.0008	...	0.0001[c]	...	8	...
Cu	...	0.008	0.43	0.0001[c]	...	80	4,300

Table VI. Relative composition of marine animals (Adjusted to NA = 100). From Sverdrup, Johnson and Fleming, THE OCEANS: Their Physics, Chemistry, and General Biology (C) 1946 by Prentice-Hall, Inc., Englewood Cliffs, N. J.

Summary

These figures are all for an unshielded reactor, and are the worst case because the concentrations are high for both sodium and chlorine. It seems desirable to shield the reactor and cut down the neutron flux to a point where only small amounts of activity are being generated in the water. What is an acceptable level of activity in the water is a mute question because (a) the dilution factors are unknown, and (b) the biological concentration of some elements may be very high, Sverdrup et al (1946). The water currents caused by thermal convection near the reactor will be of paramount importance in determining the dilution of the radioisotopes produced in the sea water. The biological concentration of the radioisotopes should be studied further to find out what concentration of radioisotopes occurs in the food chains of marine life.

In this example, we have taken the worst case with the neutron flux with no shielding to calculate the production of radioisotopes. It will be necessary to seal the reactor in a thick pressure vessel for operation in the deep ocean. Considerations as to the overall stability on the ocean floor might require a thick layer of noncirculating water as ballast for stability as well as a pressure vessel. Biological shielding can be built into the reactor, greatly attenuating the neutron flux at the surface.

Further studies of the overall problems should be continued and calculations for any possible radioisotopes should be made including studies of the biological concentration factors, as well as the amount of dilution that can be expected.

CHAPTER X

MISCELLANEOUS PROBLEMS AND POSSIBLE SOLUTIONS

Location, Relocation and Position Holding

The approximate difficulties to be expected in the accurate fixing of a bottom unit in the deep ocean and its later location for servicing, monitoring or removal are described in two papers Brown, (1962 a & b); the second of which is unpublished.

Briefly, several navigational systems are available for use near land, but only celestial navigation will at the present time allow initial siting on the ocean expanse. Any bottom search technique will obviously benefit by a close approximate fix before bottom search begins, inasmuch as the area to be traversed will vary as the square of the accuracy of the original fix. According to sources cited by Brown and also by Elmendorf and Heezen (1957), the best that can be expected for an original fix is plus or minus 1/2 mile. On relocation, this becomes plus or minus 3/4 mile. Successful search will depend upon bottom features which can be identified such as terrain features, submerged buoys, etc., none of which can usually be relied upon as permanent except major rock configurations. Brown relates the use of a taut wire system by Hughes Aircraft Company which reputedly allows movement about the fix position with accuracies of perhaps 1% to 2% of the depth; at 20,000 feet, this would allow use of bottom detection devices which could distinguish features separated to at a few hundred feet. Either this type of approach or inertial navigation is needed to insure a complete traverse over the search area.

One point of apparent difficulty not mentioned by the sources cited is that of position lag of the deep ocean probe. Even with zero current velocities, highly unlikely, any considerable velocity of the search vessel would impart drag which would make location of the probe highly uncertain.

For the submerged operating nuclear reactor (assuming no sonic signals are being emitted), the plume of warm water rising (see Chapter VIII) should provide a large, readily identifiable feature, if a suitable probe is developed. The sensor for the probe would consist of a suitable thermocouple or thermistor; its position would be less critical than other types since the plume should be of the dimension of hundreds of yards at an optimum height above the bottom. In regions of significant ocean currents near the bottom, such a system would not operate, as the warm water would be quickly dispersed if the reactor shut down. The permanence of a warm water plume following reactor shut-down is highly problematical; in quiescent waters a warmed layer might persist for days.

Chapter VII of this report considers vision and underwater television, which for a power producing (or using power stored in a battery) unit could be used at considerable range for relocation, using a point source of light.

Connection of the Power Source and Utilizing Device

Electric power generated by an unattended nuclear reactor on the bottom of the deep ocean might or might not be immediately adjacent to the device absorbing the power produced. If the using device were small and could be mounted on or suspended by buoys above the reactor, then power connections could be made at the surface and the combination lowered into place in a single group, with waterproof leads. More likely this is the situation in which for one or another reason, including size, sonic disturbance aspects, etc., the using device must be located on its own foundation and anchorage some distance from the reactor. If so, either both units must be lowered simultaneously and permanently coupled, or they must be connected at at least one end under water after both are in place.

Instrument cables are available which reputedly can be connected in situ without severe electrical leakage through a film of trapped salt water. The power device might use power pulses of several thousands of amperes and leakage could cause severe arcing. It is believed that the technology is currently such that one or more manufacturers can fabricate plug-in cable connectors which will express most of the trapped water and perhaps have provision for vulcanizing or sealing with a suitable epoxy resin, then internally desicating. Coupling of a suitable heavy cable conceivably can be accomplished if a suitable manned underwater capsule can be positioned near the power using device and equipped with minimum manipulators. See the following section. It is possible that the bottom operation might be reduced to this single coupling operation accomplished with a relatively immobile vehicle such as the Trieste. The couplings for large power and the necessary mechanical devices to lead in the mating parts, forcefully expel water, etc., are not known to be available; a development would probably be necessary.

Deep Ocean Service Vehicles and Manipulating Devices

Two studies covering these aspects of bottom construction, Phelan (1963) and Taylor (1962), have been made and results published recently. They have been reviewed. Briefly, vehicles and manipulators are available or under design and construction which will perform single, simple acts such as are described in the previous section, but no experience record of a finished unit which can with certainty accomplish the minimum feats at 20,000 feet depth or greater and with any bottom condition. Unless further test and development work is done in the area, the site location and frequency of inspection probably would have to be dictated by the technology at the time of emplacement.

Reactor Monitoring

There is no known precedence for periodic monitoring of a power device under remote, ocean bottom conditions, but is apparently less of a problem to approach, connect small instrument leads and take readings from internally mounted nuclear and thermal monitoring instruments than to connect and waterproof heavy power cables. Some evaluation, at least under laboratory pressure vessel conditions, should be made of commercially available instrument leads.

Alternate to the scheme of having a deep ocean manned vehicle approach and make readings from installed instruments would be a completely automatic system which would, on sonic signal from the surface, relay readings through a sonic telemetering system to the monitoring ship. Such a system might be less expensive than on-site operation from a deep ocean vehicle.

Catastrophe Areas for Bottom Mounted Equipment

Over some parts of the ocean's bottoms, earthquakes are known to cause periodic mud slides, rock slides and particular turbidity currents of unstable sediments. Such areas, Elmendorf and Heezen (1957), must be largely avoided by telegraph and telephone cables. An upright reactor of large sail area would be expected to be even more susceptible to damage, and areas of known activity must be avoided. The reference cited discusses the problem at length, and gives maps, particularly complete for the North Atlantic. Areas of known frequent bottom movement are not suitable for the location of bottom mounted mechanical equipment. The causes and conditions for formation of turbidity currents, etc., are briefed in Chapter I of this report.

Ocean Currents

Sverdrup, et al (1946), give an excellent acount of the cause and approximate scale of ocean currents due to density differences, tidal action and surface wind friction, and concludes that for the deep ocean only the first cause is important. Even here, density differences are so small that standard techniques for predicting velocities based on pressure measurements, etc., are not reliable, and such calculations as must be made must be based on observed temperature and salinity measurements, from which possible current velocities may be calculated by well established but not simple techniques. Site exploration practices should include periodic checks of ocean currents inasmuch as periodic, unexplained flow is known to occur. Frequently photographs of the ocean's bottom show ripples and ridges caused by significant bottom currents in areas thought to be still water. Currents are discussed in Chapter I, but their effective results in causing lateral forces on bottom equipment is not discussed at length in the chapters on anchoring. Further study and perhaps extensive measurements over long periods are needed in this area, before actual operational devices are placed on the ocean floor.

Temporary Power Storage for Deep Ocean Sites

The possibility that some applications of power in the ocean and particularly on the bottom will be intermittent, makes the consideration of interim storage desirable. Two systems of electrical power storage for DC are available. First and highly desirable where pulsing is fairly frequent is capacitative storage. No source of information on practicability of using large condensers is known. If a tuned circuit can be arranged, this application is particularly desirable in that switching is accomplished by the tuned circuit, and the reactor could operate continuously at a reduced rate; its size, life and cost would be optimized. Similarly effective would be the use of storage batteries at the site of the using device, thus reducing the power transmitted over cables to the reactor. The problems are being considered, Horne (1963), but the feasibility not established at the present time. This arrangement would require periodic switching of relatively large currents, and the switch gear and its control circuit an undesirable mechanical complication.

Far less attractive than either of the two arrangements briefed would be that of providing 100% capacity during on pulse time, and either letting the power generator receive the brunt of periodic interruptions or switching to resistor banks and dissipate the power during the off time. Dissipation of the heat would not be difficult but switching would be. Worse yet, the reactor would have to produce large amounts of unproductive power, increasing its size and reducing its life. The control problems would be complicated, so it is highly probable that dissipation of the excess power during the off cycle in resistor banks submerged in water would be necessary.

Magnetic Location Device

The null-indicating magnetometer is capable of measuring a magnetic field to within one (1) milligauss, and would make an ideal instrument for detecting a large mass of iron, such as a nuclear reactor, on the ocean floor. The instrument was developed for degaussing during WW II, is very reliable and is easy to operate by a trained technician.

A shipboard magnetic detector was developed for the PC class of ship during World War II. Two helical coils were wound around a wooden form and located in a transverse plane in a ship. One of the coils was located as far forward as possible in the ship while the second was located as far aft as possible. One coil was wound in a clockwise direction and the other in a counterclockwise direction, and the two coils connected in series with a recording millivoltimeter. When the ship passed over an area of the ocean with a uniform magnetic field, the resulting voltage was zero, and the millivoltimeter did not indicate a voltage. When the ship approached a magnetic object, i. e., a submarine, the rate of flux increase was greater in the nearer coil than that in the remote coil. Consequently, a differential voltage was generated and indicated by the millivoltimeter.

It is suggested that a modification of this technique might be used to locate an underwater mass of magnetic material, namely, a nuclear reactor.

A long right circular cylinder would be fabricated from a non-magnetic material. Transverse helical coils would be wound and placed at opposite ends of the cylinder. The cylinder should be designed for towing behind a surface ship near the bottom and should have a low drag on the towing line. The helical coils would be connected in series so that the induced voltage would tend to counteract each other when moving in a uniform magnetic field, and lead wires brought to the surface along with the tow line. The lead wire when connected to a recording millivoltimeter would give an indication of the region of strong pertubations in the earths magnetic field.

SUMMARY

The preceding chapters briefly describe the principal features of the deep ocean environment insofar as they will probably affect the placement and operation of an unattended nuclear reactor on the deep ocean floor.

Corrosion and necessary coating techniques are well understood for most ocean situations; while the deep ocean bottom situation is not so well documented, it is believed that current technology will allow fabrication and a reasonable life. Coating schemes used, for example stainless cladding, may be more costly than necessary, but capable of sufficient life for the purpose proposed. The heavy reactor vessel necessary for testing and operation under a variety of conditions, should provide a long containment of reactor core materials after the useful life of the reactor is passed, in the event that it is uneconomical, undesirable, or impossible to retrieve it.

Foundation and anchorages are outlined, but are in the experimental stage. It appears that the two systems for foundations proposed are based on conservative engineering practices viewed from the standpoint of conventional engineering practice on the surface; however, neither has been demonstrated.

Handling, placing and retrieving of a heavy package appears to be merely an extension of the present arts of ocean operations, but size, shape and packaging for this phase of the operation may determine much of the original package design. The illustration provides for handling weights far in excess of those probably necessary, but through a small well in a special ship's hull. The plan area of the working reactor would either have to be kept very small, its shield would have to be lowered separately, it would have to be handled over the side of a ship on cranes of lesser capacity, or a special ship with a very large well would be necessary. The approach used will have a major bearing on operation costs.

Underwater vision and television monitoring appear to be feasible at almost any depth from a pressure containment and electronic standpoint, but it is not at all obvious how a camera can be suspended from the surface in such a manner as to view the appropriate scene. The problems are similar to and perhaps part of those of underwater search for the reactor.

Location of a reactor originally in the open ocean can at the present time be done perhaps with 1/2 mile. With the same tolerance for relocation, plus or minus 1 mile will lead to a search area of several square miles, using either visual observation, a heat-sensitive probe, combinations of sound transponders, etc., or perhaps new techniques such as use of very sensitive magnetometers. Any but the sound techniques would require trailing of a probe at depth and it is not at all certain or proven that they would be useable for a systematic search because of lateral drag forces on the cable making the location of the probe highly uncertain. Other systems involving surfacing buoys on command from the surface through sonic signals, etc., are possible but might cause difficulty in operation because of reflecting surfaces in temperature or salinity stratified waters. Certainly a combination of alternate systems would be required to obtain any reliability.

The ocean depths appear to be rather ideal heat sinks; the effect on deep temperatures for even prodigious quantities of heat release is calculated to be trivial. With any currents at higher elevations, rapid dispersal of warm waters would be expected. Lateral currents will form under the influence of Coriolis accelerations if the vertical velocities become significant, so even quiescent waters should dissipate the heat over large areas rapidly. Heat transfer of the types which might be involved are well understood, and fairly direct design with simple experimental verification of finished prototype convectors should be possible at little expense. The experimental problems connected with performing an experiment releasing large amounts of heat in the deep ocean appear to be within reason but very expensive. Location of a bottom release of large amounts of heat from a submerged volcano would be instructive in assessing the total problem.

CONCLUSIONS

It is concluded that:

(1) Within the constraints applied by the reactor and the power conversion state-of-the-art, assembly, handling and placement of a bottom-mounted unattended nuclear reactor appear to be within the scope of current technology provided its size is controlled during design; weight probably will not be a problem.

(2) Provision of suitable foundations and anchorage will require considerable development unless any but selected firm bottoms are used. Operational feasibility of proposed designs in any case needs to be proven.

(3) Successful placement, monitoring, and perhaps connection of separate major components appears to be dependent upon some sort of small, maneuverable submersible for the depth selected, but minimum manipulators to actuate prefabricated couplers, etc., will be necessary.

(4) Many systems appear to have merit in re-location of the reactor on the bottom, but no precedent is available to insure success of a given system.

(5) With a suitable foundation to maintain the necessary attitude

and altitude above the bottom, convectors can be designed to reject the large amounts of heat necessary; the ocean can ordinarily accept such quantities of heat without surface disturbance or formulation of large permanent bodies of unusually warm water; so long as the water is heated sufficiently to be buoyant, lateral currents will form tending to dissipate the warm water.

(6) Bottom search for re-location appears to be the most difficult present problem, but major bottom features may be useable for cite identification in many cases, provided that sites with such features are otherwise desirable.

(7) Large parts of the ocean's bottoms are subjected to turbidity currents, earthquakes, etc., which will make them completely unacceptable as sites, especially since the using devices for the power generated will perhaps be capable of initiating slides.

(8) Corrosion and coating problems, while largely unknown, can be overcome in a prototype reactor by provision of extra thickness materials as a corrosion allowance or by cladding. Additional fail-safe protection in the form of sacraficial cathodic protection should probably be provided.

(9) Many major problems outlined in the text and summarized above and in the conclusions must be solved and their solutions demonstrated before placement, servicing and operation are practicable.

RECOMMENDATIONS

Of the problem areas considered in the report, the following are recommended for further study. The first category consists of those areas which are being studied now at other activities. The second category includes those areas for which further investigation, design, and testing within this task is proposed.

Category I:

(a) Relocation and systematic bottom search.
(b) Vision and remote television.
(c) Temporary power storage.
(d) Remote communications.

Category II:

(a) Over-the-side handling at sea - specification of a technique for complete design based on an actual reactor of given weight, size, and shape.

(b) Anchorages - design and test on a suitable scale of the best anchorage systems known or visualized.

(c) Foundations - design and test on a suitable scale of foundations known or visualized for worst bottom conditions.

(d) Bottom operation construction or assembly techniques - further specify minimum requirements for bottom assembly of surface-mounted components; available components; and others in need of development.

(e) Ocean circulation, heat rejection and heat transfer - study on a model, preferably large scale, to allow projection to full scale on ocean bottom.

(f) Marine fouling and animal attack - specify best known protective systems for an actual reactor, based on findings of Chapter II and studies under way at NCEL or elsewhere.

(g) Position holding - survey available demonstrated techniques, analyze critically and make a firm recommendation for most practical system for position holding on surface above a bottom work site.

It is recommended that state-of-the-art studies for the items of Category I be assigned for completion in June 1964.

Those areas listed in Category II above should be investigated, either by consultation, library research, or theoretical and experimental studies as indicated. It is believed that demonstrated operational proficiency is needed with regard to each problem area to insure the success of an undersea reactor.

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