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FACTORS INFLUENCING THE DESIGN AND OPERATION OF POTENTIAL OFFSHORE SUBMERGED STORAGE FACILITIES

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FACTORS [illegible] DESIGN AND OPERATION OF
[illegible] STORAGE FACILITIES

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By

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I. INTRODUCTION

The dynamic evolution of offshore oil development in the Gulf of Mexico in the last decade with its elements of high costs, requirements for new techniques, and enormous risks has again demonstrated the fortitude of the oil industry in its continual search for new sources of petroleum.

In this new frontier there are no established limits. Drilling in depths of water up to 600 feet have been predicted,[1] and nearly each succeeding publication of trade journals includes a reference to a new location, both foreign and domestic, where a search for offshore oil is being made. The potential areas for offshore oil must truly be interpreted in terms of world-wide operations.

The challenge of finding oil up to depths of 100 feet of water has been met, but in the words of a Special Report published in the February 22, 1957 issue of Petroleum Week, "The glamor days are over; the make-it-pay stage is here".[2]

Foremost among the many "make-it-pay" problems facing the operators is the search for the most economical and practical method for gathering and moving the produced oil to the refinery.

Operations in marshlands and inland waters are not new to the industry and the problems of gathering and transportation of the oil in these areas have been successfully met by the combined use of elevated storage (supported by either piling or a submerged hull), barges, and pipelines. These methods have been extended to operations in shallow

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[1] References are listed in the Bibliography.

coastal waters, and it is generally agreed, despite the high cost, that a combination of these methods offer the only practical solution in water depths up to about 40 feet.[3]

As the water gets deeper, the economic problems become greater. The increased distance to shore for either pipelines or barges advances the price of transportation until the possibility of foreseeable economic production becomes highly questionable.[3]

The search for new methods to overcome this problem is continuous, and it has been reported recently that the use of submerged storage in combination with tanker or barge loading is a strong candidate.[2,3]

The basic idea of submerged storage is not new. Patents pertaining to this concept date back to 1916 and the records of the U. S. Patent Office show at least twenty other generally related inventions. The submarine, in a modified sense, can be considered as an engineering application of submerged storage since diesel oil is stored in tanks outside the pressure hull.

Increased emphasis regarding this method of storage has been noted in recent months. Current articles in the April and May, 1957 issues of Offshore and the June 17, 1957 issue of The Oil and Gas Journal describe proposed types of facilities for offshore use.[4,5]

Despite this record, the published literature does not substantiate any operational use to date of a system designed for this purpose, and there are no known sources of composite evaluation data available to the operator who may consider this method. In the preliminary review by the author, divergent design approaches by different inventors and authors to many phases of the subject were observed and very few background data,

if any, were provided as a basis for decision. This condition is not unreasonable, for any inventor or architect must assume a given set of conditions to fix the limits of the design. However, in the final analysis, it is the operator who must provide the specifications and evaluate the design for his particular operations.

In the evolution from first consideration to practical adoption, the operator's decisions can be reached in one of two ways. He may attempt to evaluate a proposed design in terms of known or expected operating conditions, or he may elect to provide limiting specifications from which the architect will prepare a design, after which a later evaluation by the operator will be made. In either case it is essential that the operator have a clear concept of the factors which can influence the design, installation and operation of the device. The criteria may not be constant and the resolution of some variables must be left to the designer, but information regarding the relative magnitude and importance of such variables must be available. A single source document containing such data is always desirable.

This study of submerged storage for offshore production is directed to the above need. A strict civil engineering design study for a specific application or a quantitative analysis is not intended. First, such a study would be beyond the scope of the training of the author, and second, it is considered that different operating conditions, weather, and other factors would preclude any standard design. Rather, it is hoped that this study will provide useful qualitative criteria to the operators who may consider this type of storage.

This study will begin with separate discussions of the essential engineering factors and fundamentals which would be considered in the design and operation of a submerged storage system. At the present time there are only four types of proposed systems for offshore production known to the author; undoubtedly there will be many more in the future. The patent files include many ideas which an operator may wish to review. Thus, a qualitative discussion of the fundamentals is considered appropriate to provide a basis by which any new proposed system may be evaluated.

In the discussions of the fundamental factors, some remarks will refer to ranges of liquid petroleum, fuel connections, etc., which are beyond the scope of offshore production operations. The inclusion of these added details are considered appropriate for an operator in the industry or military who may wish to consider other applications for this type of storage.

After presenting the essential design and operating factors and their fundamental principles, a correlation will be established between offshore production operations, the general feasibility of submerged storage, and the basic types of systems which have been recently proposed for these applications.

II. LIMITS OF THE PROBLEM

The term, submerged storage system or facility, as used in this study includes any non-self-propelled vessel, tank, container or structure which may be constructed, installed or anchored in such a fashion that the principle part of the system, excluding pipeline connections, will be submerged below the surface of the water under operating conditions.

The discussions in this study will relate primarily to a totally submerged system but the following deviations are considered to include the same basic principles:

1. A combination system wherein a separate but smaller, additional storage compartment is supported above the water by the same foundation, with a fuel pipeline or conduit connection leading to the principle submerged compartment which in turn extends to the foundation at the bottom.

2. A vertical system with a storage compartment extending from the bottom to a point above the surface where it supports a platform.

In the approach to this study, the following assumptions are made:

1. That, excluding any economic considerations, the basic concept of submerged storage is feasible purely from an engineering standpoint.

2. That the product to be stored will be liquid in form.

3. That the system will be located in offshore navigable waters of at least 50 foot depth.

4. That for the foreseeable future, or at least within the next decade, oil pipelines will not extend outside the 10 fathom curve in the Gulf of Mexico. This is substantiated by the fact that only a few pipelines have been laid to serve the fields close to shore in shallow waters

and very little optimism exists in published reports for extensions to deeper water. With prices of $13.00 and over per foot for an 8-inch line and considering the potential hazards in both the installation and maintenance operations, the feasibility is highly questionable.[3,6,7,10]

III. WEIGHT - VOLUME - SPECIFIC GRAVITY RELATIONSHIP

A study of the characteristics of any submerged storage system would logically begin with the forces necessary to submerge the storage vessel and to hold it in place under static conditions. A review of Archimedes' principle will indicate that the ability to submerge a vessel containing a liquid product will depend on the interrelationship between the weights, volumes, and specific gravities of the solid and the fluid product, and the specific gravity of the water in which submerged.

The determination of required forces involves relatively simple physics for any one given set of conditions. However, the designer and the operator will not be faced with an ideal situation but a combination of variable and changing conditions. It is these factors which make the problem more difficult.

In the course of investigating these conditions the following determinations should be made:

1. What are the variables which can effect the buoyancy forces?

2. What are the variables which can effect the weight or submerging forces?

3. What is the relationship between the two in a constant volume system? (A constant volume system is one in which the storage compartment is a rigid container and the stored products are not subject to sea pressure. Any space not occupied by the product will be filled with vapor.

4. What is the relationship between the two in an internal displacement system? (An internal displacement system is one in which the bottom of the storage compartment is open to sea pressure and any space not occupied by the oil will be filled with sea water.)

Discussions of the above points will be limited to a rigid structure which is completely submerged. Later discussions under this heading will include flexible containers and structures which extend above the water line.

A. Variations in Buoyancy Forces

The buoyancy force of a submerged vessel is equal to the weight of the water displaced and therefore is a function of the density and volume of the water displaced by the vessel and its contained product.

The densities of inland fresh water and sea water are recognized to be different but often the individual values are commonly considered to be constant. This assumption could lead to substantial inaccuracies in the calculation of the buoyancy force, especially for sea water.

The density of sea water depends primarily on two factors: temperature and salinity. As the temperature decreases, the density increases; conversely, as the salinity decreases, the density decreases.

Density variations with location and depth would be expected, but equally important, considerable variations in a single location have been recorded by the U. S. Coast and Geodetic Survey.[8] A minimum reading of slightly less than 1.000 for some locations and a maximum of slightly greater than 1.030 for others have been recorded. Recorded readings at a number of locations have shown a variance of about 0.020.

These variations can be significant and must be planned for. A variation of 0.020 would result in a change in the buoyancy of about 7 pounds per barrel volume, or about 175 tons for a 50,000 barrel storage facility when completely filled. (Note: Simple calculations involving

weights and buoyancy are used to merely show relative magnitudes. These include a 2000 pound ton, 350 pounds per barrel of fresh water, and the volume of the tank's hull thickness or attachments is neglected.)

Since the volume of water displaced is the other variable in buoyancy, this will depend primarily on the size of the rigid submerged storage container. Slight variations in the hull size may be caused by compression due to hydrostatic pressure but this will be ignored in the discussion.

In a submerged constant volume system there is no pressure contact between the sea and the oil, and the volume of displaced water will remain constant regardless of whether the compartment is full, one-half full, or empty. As long as the container remains fully submerged, and assuming a constant sea water density, the gross buoyancy will remain constant. For a one barrel container in sea water of specific gravity of 1.020, this upward force will be equal to 357 pounds (350 lbs/barrel x 1.020).

It is important to note the difference in an internal displacement system. From the definition, any space not occupied by oil will be filled by sea water. Neglecting any slight volume of the shell, the buoyancy force would be zero when the compartment became void of oil since the sea water has freedom to occupy all spaces in the submerged container. If oil is forced into the top of the one barrel storage until it is one-half full, one-half barrel of sea water is displaced. The weight of the sea water displaced is equal to $\frac{1}{2}$ x 357 pounds or 178.5 pounds and the gross buoyancy force is the same. In a similar manner, when the compartment is filled, the buoyancy force will be equal to 357 pounds. It should

be noted that gross buoyancy does not depend on the gravity of the oil.

The design of a submerged storage will normally be based on maximum buoyancy conditions. This will occur in the heaviest sea water when the storage is filled to capacity. Unlike surface storage, allowances for expansion due to evaporation and temperature variations are rarely required since the water temperature will normally be less than the surface or pumping temperature. One exception to this has been noted in the study of various types of system. In a system proposed for world-wide military operations, a barge is used to transport fuel in addition to serving as a storage tank when submerged on the site.[9] In this case, some expansion may be expected during transportation, and it is necessary to reserve part of the total capacity for expansion.

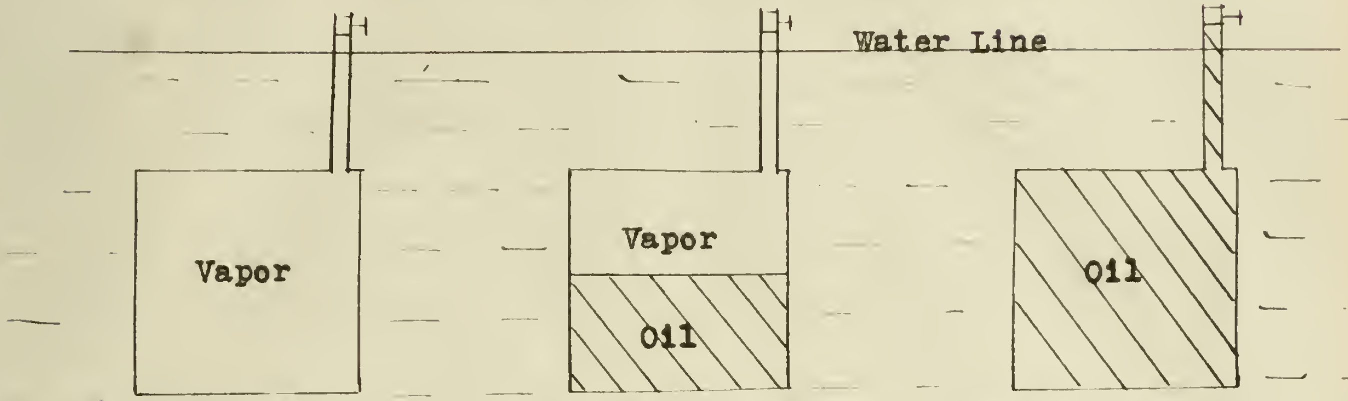
Summarizing, it can be said that the buoyancy force of a submerged storage system is a function of the density of the sea water and the volume of the water displaced by the submerged part of the system. In a constant volume system the buoyancy force will vary only with the density of the sea water, but in an internal displacement system, it will vary with both sea water density and the amount of oil stored. Examples of buoyancy forces for both systems, assuming a constant sea water density, are depicted in Figure 1.

B. Variations in Submerging Forces

The forces tending to submerge a vessel depend on the combined weight of the vessel's structure, the solid ballast, and the contained product. To sink the vessel the sum of these weights must be greater than the buoyancy force. The amount by which the sum of these weights exceed the buoyancy is known as negative buoyancy or it may be called the sinking force (Weight (W) - Buoyancy (B) = Sinking Force (S)).

Examples of Buoyancy Forces
In Sea Water of 1.020 Specific Gravity

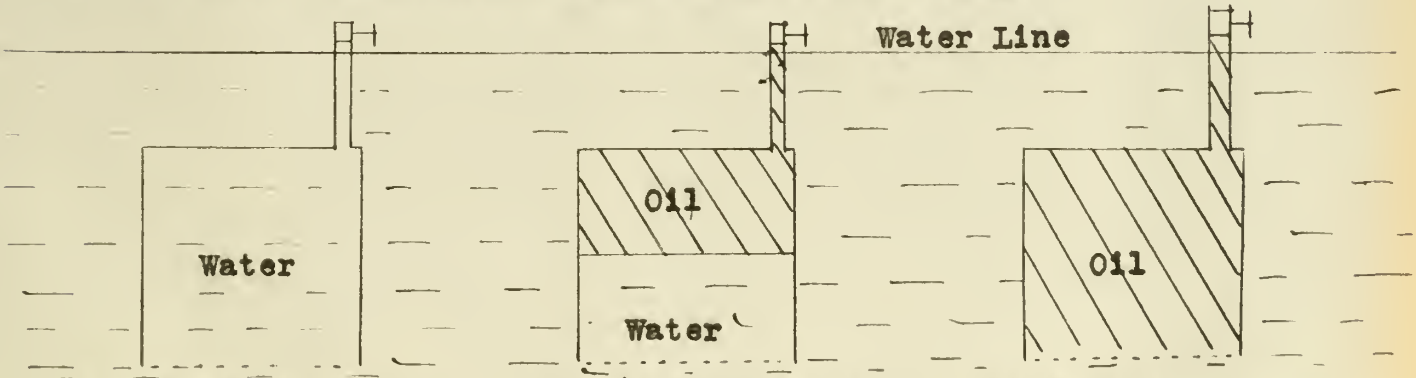
1. Constant Volume System (One Barrel Volume)



(a) Empty of Oil (b) 1/2 Full of Oil (c) Full of Oil

Note: Buoyancy force of constant volume system is the same under all conditions. For a one barrel system, buoyancy force (neglecting shell) equals 357 pounds in sea water of 1.020 specific gravity.

2. Internal Displacement System (One Barrel Volume)



(a) Empty of Oil, Full of Sea Water, Zero Buoyancy Force.

(b) 1/2 Full of Oil, 1/2 Full of Sea Water, 178.5 Pounds Buoyancy Force.

(c) Full of Oil, Buoyancy Force Equals 357 Pounds.

Note: In this type system the bottom of the tank is always open to sea pressure and the volume of water displaced or buoyancy force will vary with the volume of oil. Thus, maximum buoyancy force will exist when the system is full of oil.

Figure 1

It has been explained that the maximum buoyancy force for the typical one barrel container would be equal to 357 pounds with the sea water gravity at 1.020. A vessel with a combined weight of 357 pounds would remain submerged at equilibrium at any depth, thus an additional weight is required. For purposes of analysis, a minimum of 4 pounds sinking force per barrel volume will be arbitrarily selected for a static system. This would represent a typical differential necessary to compensate for slight variations in specific gravity of the sea water. Thus, a total of 361 pounds submerging force would be necessary to sink the typical barrel volume (357 + 4) to the bottom.

The primary variable in determining the submerging force, and consequently the weight of the vessel structure and ballast, is the type of product and its specific gravity. To show the effect of gravity variations, a range from 20 degrees API (0.93 specific gravity) to 70 degrees API (0.70 specific gravity) will be used. These would represent practical limits if a submerged storage were to be used with different types of products, crude and refined, under various operating conditions.

While it is highly unlikely for any one operator to encounter this wide range of conditions, wide variances in gravities may be reasonably encountered, and a mobile system would be more practical if designed for different conditions.

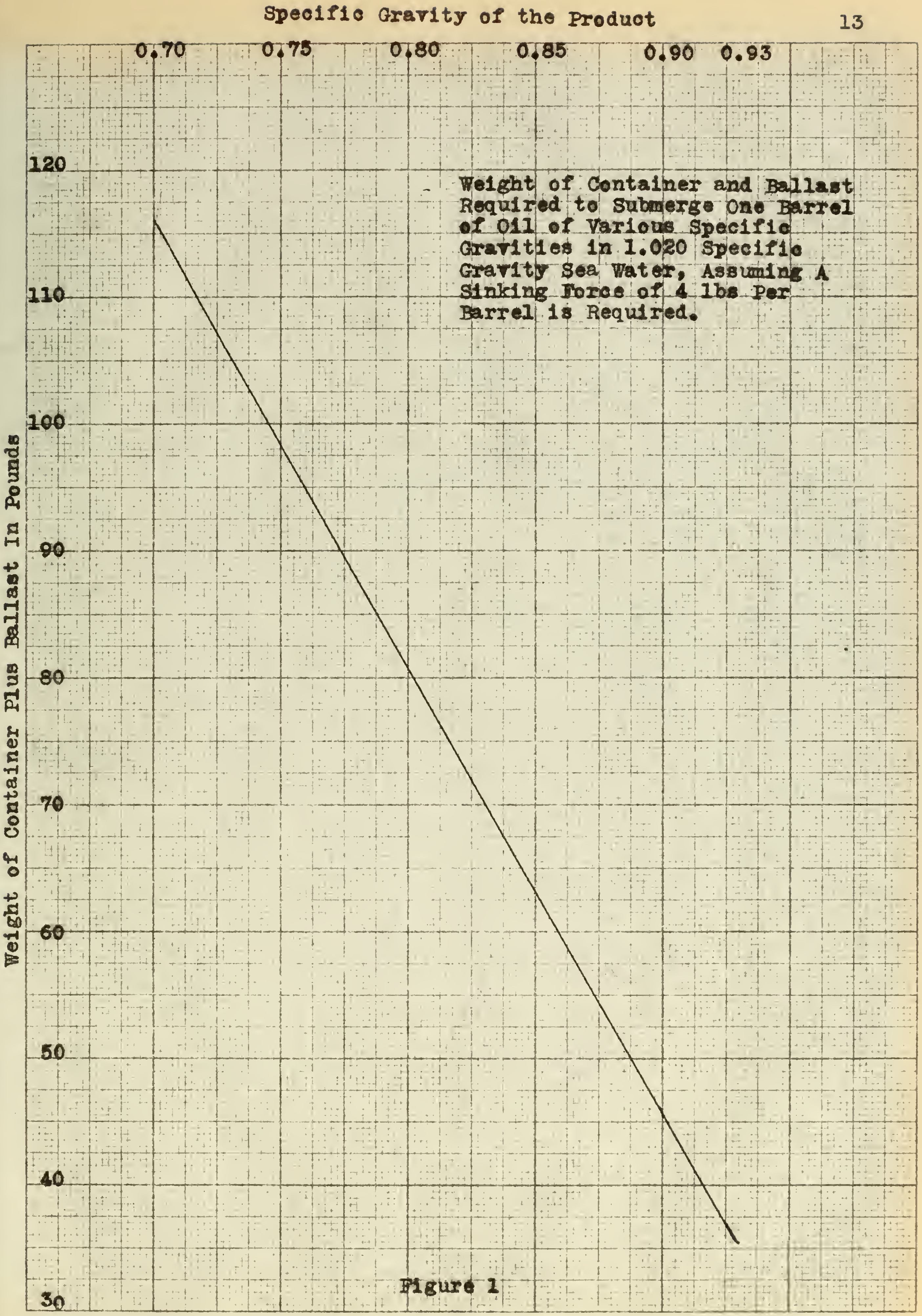
The magnitude of specific gravity variations can best be demonstrated by analyzing the extreme assumed conditions. When completely filled with a fuel of 70 degrees API (0.70 specific gravity) the oil would weigh 245 pounds (350 x 0.70) versus 361 pounds buoyancy, or a deficit of 116 pounds to be made up by the weight of the container and

ballast. For a 50,000 barrel system the weight of the container and ballast required would equal 2900 tons.

At the other extreme condition when 20 degrees API fuel is stored, the deficit would be only 35.5 pounds per barrel volume, or 888 tons for a 50,000 barrel system. In Figure 2, a plot of deficit weights to be made up by the container and ballast versus specific gravity is included between these limits for a one barrel system. This plot will show that the combined weight of the structure (vessel) and ballast must be increased approximately 17.5 pounds per barrel for an increase in specific gravity of 0.05. In terms of a 50,000 barrel system, this net increase would approximate 437 tons for an increase of 0.05 specific gravity of the oil, which could be quite substantial in field operations where a system was designed for a heavy product and then later used to store a much lighter product.

The ratio between the structural weights and the solid ballast is always a compromise depending on economics, degree of mobility and surface stability desired, lateral forces, additional hull structure (such as air-ballast compartments, stress members, and sectionalized compartment), weight of anchor chains, etc. Since these involve detailed civil engineering drawings and calculations, no attempt will be made to present any quantitative examples but some of the general relationships will be pointed out.

First, the entire deficit weight must be made up by solid matter if the system is designed to provide for maximum buoyancy conditions when the compartment is filled. This deficit will change with



Weight of Container and Ballast Required to Submerge One Barrel of Oil of Various Specific Gravities in 1.020 Specific Gravity Sea Water, Assuming A Sinking Force of 4 lbs Per Barrel is Required.

Figure 1

gravity of product, [illegible] it is assumed that the system is being designed for only one gravity [illegible] and the deficit is constant. The flooding of extra air ballast tanks will not help. As soon as this type compartment becomes filled under submerged conditions, it becomes neutral in buoyancy and in weight since the water has free access to flow out or in. The structural weight of the shell of such a compartment does help but this is solid matter, not fluid ballast.

Economics will dictate that the hull structure be as light as possible since heavier shell plates are not only more expensive but more difficult to fabricate into a vessel or tank. The limiting factors in determining the thickness and the design of stress members will be the type of system (constant volume or internal displacement), rigidity required in the surface, lateral forces, and possible distortion due to settling in weak soil. All of these relate to potential stresses to which the system will be subjected. The designer will generally attempt to use the lightest possible structure and then compensate for the difference in weight by solid ballast.

The operator will be most interested in the type and location of ballast proposed. As will be discussed in a subsequent section, the need for a low center of gravity in controlling submerging operations is very important and the location of the fixed ballast is the controlling factor. Detachable ballast will be proposed for some systems to hold the system down when submerged with a light fuel. This procedure can reduce the construction costs by use of thinner hull plates, but the operator must carefully consider it in terms of degree of mobility desired, depth of water, and installation costs. Transporting additional fixed ballast can

restrict the mobility and the installation is even more difficult. Mobile crane equipment will be required; the tanks must include some type of skirt or structure to hold the ballast in position; and divers will be required to fasten it in position. As a general rule, it is desirable for the system to be constructed with sufficient inherent sinking force to hold the storage on the bottom under maximum designed operating conditions.

Some patents have recommended the use of an anchor system to provide submerging force. This procedure is definitely not considered practical for the following reasons:

The discussion so far has been limited to a static system with no consideration to lateral forces of winds, waves, and currents. A discussion of the magnitude of these forces is premature at this point but it is known that these forces decrease with depth. Therefore, it is desirable to keep the storage facility on the bottom where they are at a minimum and where the resistance of the bottom can assist in preventing lateral movement. The magnitude of the wave forces can be enormous. A typical storm force against a submerged barge (100 ft. x 150 ft. x 10 ft.) in 100 feet of water has been calculated by one author as 840,000 pounds.[10]

Mobile anchor systems are normally used to prevent lateral movement rather than vertical movement, and 12 degrees from the horizontal is considered by the Navy as the maximum for efficient holding power.[11]

A degree of vertical holding force does exist, but it can vary greatly with the type of soil and the type of anchor. A thumb rule of three times the weight of the anchor is often used as the break-out force

for a stockless anchor with stabilizers in a sand bottom. The breaking strength of the chain would present no problems since chains are available which will withstand a 1.5 million pound load.[11]

No data were found regarding break-out force of steel piling, but it is assumed that they could be constructed to withstand greater break-out forces than mobile anchors.

The significant disadvantage to moored submerged systems is that the anchors would not only have to provide submerging force, but would have to withstand shock loads from waves. These would have both a horizontal and a vertical component. For these reasons, it is considered that submergence by the use of anchors would be limited to small storage - less than 1000 barrels - under extremely good weather conditions.

The above comments do not strictly apply to a piling system wherein the container is pinned down to the bottom by the piling. In this case the wave forces are essentially horizontal.

Insufficient data are available to determine to what degree piling of this type can furnish submerging force. Although an impression was obtained in a review of many articles on drilling barges in the Gulf of Mexico that in most cases the pilings were used primarily to resist lateral forces, it is believed that they could also be employed to hold the system down under conditions of maximum lifting force.

Summarizing, submerging force is a function of the combined subsurface and above water weights of the structure, ballast, and the stored product. The range of gravities of the product is the primary variable in determining the submerging force. The combined weights of structure and the ballast (fixed or detachable) should be sufficient to keep the

system submerged when filled to maximum capacity with the lightest product. Pilings are sometime used to help hold the system on the bottom, but they are usually installed primarily to resist lateral forces. Anchor systems are not considered feasible for keeping a large system submerged.

C. Constant Volume System

Some of the patents have indicated the possible use of a constant volume system. This would be a very rigidly constructed pressurized vessel wherein no pressure contact between the product and the sea water exists; and when it becomes empty of oil, the space is merely filled with vapor.

The severe limitation of this type system should be apparent. It will be recalled that the buoyancy force of a one barrel submerged system of this type will always remain constant at 357 pounds (S.G. sea water - 1.020), since the amount of sea water displaced by the constant volume is constant. Also, when the system is full of the lightest fuel, the weight of the container and ballast, from Figure 2, must equal 116 pounds per barrel volume. But, look at the situation when this type system becomes empty. The weight of the vapor is negligible and it is apparent that the entire buoyancy force must be offset by the submerging force or the weight of the container and ballast. Assuming a submerging force of 361 pounds (357 + 4 pounds sinking force) is required, a combined weight of 182 tons for the structure and ballast would be required for a small 1000 barrel system when empty.

In addition to this factor, the vessel would have to be constructed to withstand the complete hydrostatic pressure at the depth submerged.

The conditions under which even a small 500 barrel system of this type would be practical are very remote and it is not considered applicable to offshore operations.

D. Internal Displacement System

The essential features of an internal displacement system are that the oil is always in pressure contact with the sea water when submerged, and sea water will fill any space not occupied by the oil. This is the only type system considered practical for offshore operations.

One advantage to this system is that the pressure is always practically equalized at any height on both sides of the storage compartment and the shell does not have to be constructed to withstand a large pressure differential. A small differential will exist due to the necessity for restricting the size of the sea valves. Another advantage is that the oil is always under pressure due to the hydrostatic head of the water and natural discharge flow, within certain limits, will take place. However, the operator must keep in mind that a surge tank and pumping equipment will be required to displace the water when filling the system with oil.

The principle advantage with regard to buoyancy and weight is that maximum submerged buoyancy (excluding any possibility of air tanks or air pockets) will occur when the system is filled to capacity. As the oil is used, or discharged, the weight or submerging force will be reduced. However, this reduction in volume of oil will also reduce the amount of water being displaced, and since the specific gravity of the water is greater than the oil, the loss of buoyancy is more than the loss of weight. A larger submerging force is the net effect. From this, it is apparent

that the design would normally be based on maximum capacity when, under submerged conditions, the buoyancy force of the system is the greatest and a greater fixed weight is required.

In previous discussions, two facts were established; one was that the design is usually based on conditions of maximum buoyancy and the other was that the maximum submerging force or combined weight of structure, ballast, and product is dependent on the specific gravity of the product. How are these two relationships reconciled in a completely submerged internal displacement system?

First, the system can be designed for maximum capacity of the heaviest or an intermediate weight fuel. This will permit use of the lightest combination weight of the vessel structure and solid ballast. If the system were then filled with a lighter product, additional solid ballast must be attached or pilings must be used to keep the vessel submerged. Both of these methods are recommended for two different size systems proposed by the Sea Engineering and Salvage, Inc.[4] Detachable solid ballast is recommended for the small semi-temporary system and pilings are recommended for the larger permanent system.

For the operator, such as the military, who may desire a true mobile system for world-wide operations, where cranes or construction equipment are not readily available, pilings or detachable ballast are not practical. To save weight of construction and overcome this problem, a different approach was recommended in a proposed system for the U. S. Army.[9] The designer recommended that when light fuels are used the rated capacity of the system be correspondingly reduced. By this procedure the fixed weight of the vessel and ballast would compensate for maximum capacity

of the heaviest fuel of 25 degrees API, but these weights would only compensate for 50% of capacity of the lightest product of 70 degrees API. This is considered an extreme approach and is not recommended for use in offshore production applications.

Another approach is possible. The fixed weight of the system can be designed for the lightest product. This in turn will require the heaviest combination weight of vessel structure and ballast, but the cost of construction can be excessive. This method does have the advantage that sufficient static submerging force is available under all conditions and a design approaching this limit, consistent with economics, is the more practical.

For a mobile system the problem of surfacing must not be forgotten, especially for the heavier construction. Separate air ballast tanks may be provided, but positive controls must be available to insure that these tanks are completely flooded when submerged, or rupture due to hydrostatic pressure may occur. The main storage compartment may be deballasted with air after insuring that no oil is present, or flooded pontoons may be lowered, attached, and then deballasted. The essential point in this operation is to keep free-surface water to a minimum for controlling stability, thus deballasting should be confined to spaces with the minimum horizontal surface. Sectionalized compartments will aid in this operation.

The advantages of an internal displacement system have been pointed out in this section and it is considered to be the only practical method for offshore operations. The critical point in the weight-buoyancy relationship exists when the system is full of the lightest oil.

At that time, the net difference between weight and buoyancy is at a minimum under submerged conditions. Where economically possible, the combined fixed weight of the structure and ballast should be sufficient to hold the system submerged under these conditions. Detachable ballast may be used in a restricted mobile system when the operating conditions are such that installation is feasible; and where pilings are installed to resist lateral forces, they may be used to offset small variations in the over-all weight-buoyancy relationship.

E. Flexible Container System

The previous discussions have been limited to a completely submersible rigid container system. Several of the patents have suggested the use of a submersible flexible container wherein the container is held suspended under water by an anchor system.

In this type system no provisions are made for ballast; the weight of the container is practically negligible in comparison with the stored product; and the deficit between the specific gravity of the product and the specific gravity of the sea water must be offset by an anchor system.

Returning to Figure 1, it can be seen that the holding force of the anchors must range between 45 and 116 pounds per barrel volume. For a small 1000 barrel system the anchors would be required to have a minimum holding force of 45,000 pounds with the heaviest oil. This does not include any additional forces generated by wave action.

For this reason, plus the inherent danger of rupture by vessels or large marine fish, this system is not considered practical for

offshore applications.

F. Combination Storage and Platform System

The general features of this type system are the combination of a submerged storage and a structure which extends from the water bottom to a point above the water line where the structure supports a production platform.

This structure could be fixed in that it is constructed on the site out of prestressed concrete piles as proposed by Mr. Steenmeyer of the Mene Grande Oil Company.[12] In this design the entire structure is a group of six tanks, each fixed to the bottom and extending from the bottom to above the water where a large platform forms the top of each tank. (This construction will be described in more detail in a later section.)

On the other hand, the combination storage and platform could be a mobile structure as proposed by Bethlehem Steel Company.[5] In this structure a large mat supports huge corner columns which serve as the main submerged storage compartment. Separate structural members, some of which form oil conduits, extend above the surface and support an additional storage tank. The flat top of the above-water tanks serve as the production platform.

The question is, how do these additional above-water structures and storage affect buoyancy and submerging forces?

Both types are designed to operate as internal displacement systems with oil entering the top and the water access valves being located in the bottom of the structure. Thus, the maximum buoyancy force exists when the systems are full of oil, and it will be equal to the

weight of the volume of water displaced by the combined structure and oil which is below the surface. Since some of the structure and the oil are above water, the buoyancy force of this system will be less than a completely submerged system of equal capacity.

As for the submerging force or weight of the combined system, it will act in the same manner as for a completely submerged system. The total downward force will be equal to the total weights, both above and below the water.

It can be seen that a more equitable balance between buoyancy and submerging forces can be obtained by this type system. On the other hand, this present discussion is limited to a static system and this type system is inherently more top heavy and is subject to much greater forces from winds and waves. The relative magnitude of these separate factors will be presented in other sections.

IV. LATERAL FORCES

A review of the patents relating to the subject of this study has revealed that no consideration has been given by most of the inventors to the lateral forces which can act on a submerged structure. This neglect can be disastrous as proven by the results of storm and hurricane action against some of the offshore platforms in the Gulf of Mexico.[18]

Lateral forces can be defined in terms of currents, winds, and waves. Soil characteristics will also effect the ability of the structure or tanks to resist these forces without moving from location.

A. Currents

Since this study is restricted to offshore areas, the currents will not be uniform. However, a formula found in Fluid Mechanics textbooks for uniform currents against a submerged body can be used to show the relative magnitude of this force.[13]

$$\text{Drag} = C_d W \frac{V^2 A}{2 g}$$

Where: W = specific weight of the fluid in lbs/cu. ft.

V = velocity of current in ft/sec.

g = acceleration of gravity

A = projected cross-section area of structure (ft^2)

C_d = drag coefficient which is dependent on the shape, roughness, and Reynolds Number. For a given shape, the drag coefficient will

> reach a critical value and will remain fairly constant as the size of the container or velocity increases.

Assuming an average C_d value of 0.4 for a smooth cylindrical, large submerged tank and a current velocity of 5 knots (8.5 ft/sec.), it can be shown that the drag force would approximate 29 pounds for every projected square foot of area in the path of the current.

A velocity of 5 knots is considered to be a very strong current, even for the Gulf of Mexico.[14] While this force cannot be completely ignored, the magnitude would be very small in comparison to storm wave effects in most areas of operation.

9. Winds

Wind effects must be interpreted in terms of two phenomena. One is that winds are the primary source of waves; in the second case, the force of the winds against exposed surfaces must be considered. The first of these will be discussed under the heading of wave effects.

One of the advantages of a completely submerged storage system is that there are no exposed surfaces subject to the forces of winds. The operator who desires a combination storage and platform cannot ignore the winds. In an article in the 1955 issue of Drilling and Production Practice published by the American Petroleum Institute,[15] Dr. Richard J. Howe reports that the magnitudes of wind forces against offshore structures has been the subject of much controversy. He concludes that most designers use a series of average values for a 125-mph wind. These values vary from 40 to 62.5 pounds per square foot for flat surfaces and 20 to

40 pounds per square foot for circular members.

f. Waves

Any valid study of wave effects would be a comprehensive project in itself and is beyond the scope of this study. However, some of the basic fundamentals and examples of the relative magnitudes of waves forces will be presented from material included in several references concerning the Gulf of Mexico.[10,14,15,16,17]

A wave study for a particular area will depend on the meteorological and oceanographic data available together with the probabilities of occurrence of the worst conditions. These data must then be interpreted in terms of the spectrum of waves; namely, wave length (distance between successive crests), wave velocity (wave length/wave period), wave steepness (height/length), and the still water depth. The compiling of representative data for a given area is no simple task and the lack of this information complicates wave studies.

With the exception of infrequently occurring tidal waves, the principle energy of waves is in wind waves and swells. Of these, the wind waves are the most important since the swells merely represent the residue of wind waves in areas some distance from the generating area.

The three factors which govern the dimensions of wind waves are wind velocity, wind duration, and fetch (linear distance over which the wind blows). These factors are used to determine values of wave height and wave period by use of empirical formulae when statistical data are not available. As a general rule, wave periods in the Gulf of Mexico will range from 1.0 to 10 seconds with greater periods being associated

with storms. Wave heights about 3 feet are common with heights up to 50 feet predicted for hurricanes.

A definite distinction must be made with regard to the relative depth of the water in determining wave effects. All theories are based on a distinction between deep water, shallow water, and intermediate water. It is important to note that these classifications cannot be defined solely in terms of mean water depth, but must include the wave length. Deep water related to a condition when the depth of the water exceeds one-half of the wave length. With a typical storm wave length of 600 feet, deep water would begin at 300 feet of water. Shallow water exists when the depth is less than 1/20 of the wave length, which would be 30 feet under these theories. Intermediate water is between these extremes.

From a review of several references, it is apparent that all of the engineers agree that the wave forces are at a maximum just below the surface and that the magnitude decreases with the depth of the water. However, there appears to be some controversy as to the amount of decrease with depth. One source supports a theory that 95% of the wave energy is contained between the surface and a water depth of one-half of the wave length.[14] In this case, the wave forces could be substantial out to a depth of approximately 300 feet under severe storm conditions.

The wave forces exerted upon a marine structure consist of two kinds: a drag force component which is related to the kinetic energy of the water, and an inertial force component which is related to the acceleration of the water. The inertial force will predominate in all cases of submerged structures and will exceed drag force in a ratio of about 15 to 1.[14]

One of the primary factors affecting the magnitude of wave forces which the operator will be concerned with in this is the direction of the normal waves for the operational area. If possible, the shape of the structure or tank should be such that it can be secured parallel to the direction of the waves where it will present the least resisting area.

Presentation of the formulas used for calculating wave forces would require a series of various comprehensive theories and the inclusion of several graphs. These empirical calculations are very complex and beyond the scope of this study. Further, it is noted that approximate methods have to be employed for intermediate water depths which is the region in which a submerged storage would normally be expected to operate. However, to show the relative magnitude of these forces and the variations with depth, the results of some typical calculations are presented as follows:

Case 1. (From *Offshore Summary*)[10]

Given: A barge of dimensions 100 ft. x 150 ft. x 10 ft.
resting on the bottom
Depth of water - 100 feet
Wave period - 20 seconds
Wave height - 30 feet
Mass coefficient - 1.5

Calculated maximum force - [illegible]10,000 pounds

Case 2. (From *Offshore Summary*)

Given: A barge of same dimensions as Case 1 resting on
the bottom.
Depth of water - 40 feet
Wave period - 20 seconds
Wave height - 30 feet

Mass Coefficient - [illegible]

Calculated maximum wave force - [illegible] pounds

Case 3. (From study of a proposed submerged storage system by Mr. [illegible] of [illegible] Grande Oil Company. Tank proposed for Lake Maracaibo.)[12]

Given: Cylindrical tank of 13½ feet diameter, 114 feet high

Depth of water - 100 feet

Wave height - 6.28 feet

Wave length - 88 feet

Mass Coefficient - 1.71

Wind fetch - 20 miles

Assumes force will act at all points obliquely at 45 degrees.

Calculated maximum wave force - 419,160 pounds

It is not intended to imply that forces of this magnitude will be encountered in all areas of operation or that a storage must be installed to withstand these extreme wave effects. These calculations are presented to merely show the relative importance of storm conditions. It is evident that a study of these variables is necessary in the planning of a submerged storage system.

D. Effect of Soil Characteristics in Determining Lateral Forces

Any study regarding potential lateral forces for a given area should include a concurrent investigation of the type of soil. Uneven

bottoms, reefs, sand bars, and the slope of shelf are conditions which will have some effect on the ultimate wave forces. Equally important is the shear strength of the soil.

The shear strength is an essential factor in determining the method to be used for resisting lateral forces. The coefficient of friction between the bottom and the submerged structure should be interpreted in a similar manner. These values will normally range from a low in mud or silt to a high in compacted sand. In the softer bottoms a greater degree of resistance must be provided in the anchor or piling systems.

E. Methods for Resisting Lateral Forces

The significance of the above discussions regarding lateral forces must be interpreted in terms of the type system to be used to resist lateral movement. The problem is not unsurmountable for successful use of the submersible drilling barge has been experienced in offshore operations.

Difficulties have been experienced in keeping these barges stationary under hurricane conditions,[18] but a potential difference exists between a drilling barge and a completely submerged storage system. In the drilling barge the structure in all cases extends from the bottom to a platform erected above the water with considerable weight concentrated on the platform. It is therefore subject to the forces of winds and surface waves and to the forces of [illegible] water [illegible] throughout its entire height. Second, the inherent function of the drilling barge with its connection to a conductor drill pipe precludes any movement over a couple of feet for successful operation.

A completely submerged storage system, on the other hand, would have a much lower profile and would not be limited to such small variations in lateral motion. The operator who wishes to consider the combination storage and platform must insure that the potential additional forces against this type structure have been included in the design calculations.

In a previous subsection, II B, the disadvantages of the use of an anchor system in the submerging of a vessel were pointed out. It is believed that the above comments regarding wave effects prove conclusively that sufficient negative buoyancy is needed not only to submerge the vessel, but also to assist in resisting lateral forces.

The precise system to be used for resisting lateral motion of a submerged storage system cannot be determined until the conditions under which it will operate are analyzed. In addition to soil conditions, the degree of mobility desired will affect the decision.

For a system with a large degree of mobility the use of sufficient negative buoyancy or sinking force would be given first consideration. Several offshore drilling barges use this principle, and the Kerr McGee Rig 46 is claimed to prevent lateral slipping by its shear size (202 ft. x 242 ft.) and the open spaces between members sitting on the bottom.[19]

A study of a proposed system for world-wide military operations suggests that a 200 ton sinking force should be sufficient for a 50,000 barrel mobile storage system without use of anchors.[9] This sinking force is based on an assumption of a 2-knot current acting against the hull; no other lateral forces were apparently considered. In view of the potential wave effects under some conditions, this assumption is considered

entirely insufficient.

Supplementary devices have been used by many of the offshore operators for drilling barges. Some have added stabilizing pontoons or caissons actuated by hydraulic rams or air jacks which will press against the floor of the ocean to hold the rig rigidly in place. Others have pinned the barges to the bottom by use of piling.[19]

Different methods are recommended for the two-size systems proposed by the Sea Engineering and Salvage, Inc.[4] In the small 5700 barrel tank system the techniques include three devices for providing sinking force and resisting lateral motion. The tank is jetted 10 feet into the mud bottom (a common condition found in the Gulf of Mexico), three anchors and mooring chains are used, and prefabricated reinforced concrete blocks are lowered and attached to an anti-scour skirt of the tank. In their larger 84,500 barrel tank, they propose to use piling driven through a template.

It is indicated that the combination storage and platform system proposed by the Bethlehem Steel Company will have sufficient sinking force to hold it in place under most conditions.[5] This system also used a large mat with open center sections in the bottom of the structure. The author describing this system reports that a special clamping device (not described) may be added when the system becomes a permanent installation.

Since the fixed installation proposed for use in Lake Maracaibo is constructed by driving vertical piling into the bottom and then connecting these together to form a tank container, the resistance against lateral motion will depend on the shear strength of the soil and the

strength of the piling.

It is evident that a complete study of the potential lateral forces for a given area is needed before the exact design is fixed. The operator must insure that these factors have been considered.

V. SOIL BEARING CAPACITY

The effects of soil characteristics on lateral forces have been mentioned in the previous section. Bearing load capacity of the soil is another factor which the operator in particular must consider.

There are many areas, especially the Gulf of Mexico, where the load capacity is of great importance. The soil in this area has been described as young in a geological sense with little strength, lack of uniformity, and high water content.[20] In all areas of potential operations a preliminary survey of the bottom for the proposed site is considered essential.

For mud bottoms, the possibility of the storage system sinking completely below the normal bottom level exists; and in shell reefs or rock bottoms, unequal settling could cause distortion and unequal stresses in the tank structure. In all cases, the slope must be considered to insure maintenance of stability.

In areas of "hard" bottoms where no settling is expected, the only requirement will be to find a level location. The depth of mud above a good bearing surface will be the criterion in soft bottoms.

VI. CONTROL OF SUBMERGING AND SURFACING OPERATIONS

The method of control of submerging and surfacing cannot be limited to a technique which merely changes the inter-relationship between buoyancy and weight as discussed under a static system. A means for regulating the rate of descent and ascent to prevent damage to the hull must be provided, but more important, positive control over the vertical stability of the system must be maintained.

The use of water ballast to change the over-all weight-buoyancy relationship for submergence is an accepted practice. Control of the influx of water during submergence and expulsion of the water ballast for surfacing can be handled in two ways: (a) controlled air venting for sinking and use of air pressure for deballasting, or (b) use of pumps. A combination of the two methods also can be used, but the pumping system is considered too slow for any practical operation involving a large storage. In the air system, valves located on the vent line are used to control the rate of ballasting or deballasting.

Maintenance of vertical stability can present a substantial problem and the principles must be understood by the operator as well as the designer. Stability of a vessel in water depends on three basic factors: the location of the center of gravity (designated as G), the location of the center of buoyancy (designated as B), and the righting moment.

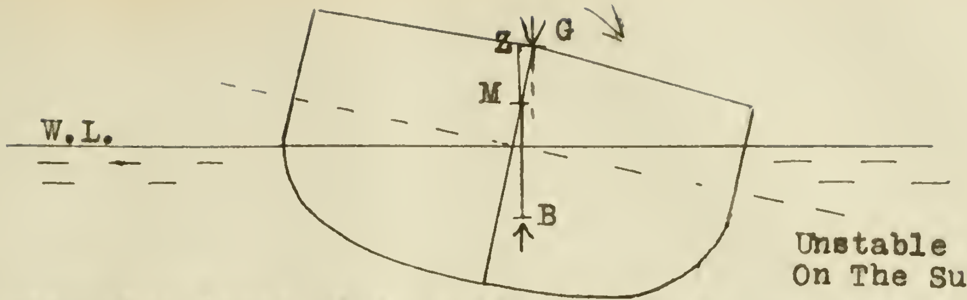
The definitions of the center of gravity and the center of buoyancy are commonly known. The relationship between the two in controlling stability is less understood. Under all conditions the resultant

upward line of force acts through the center of buoyancy and the resultant downward line of force acts through the center of gravity. When a vessel is at rest in a vertical position, these lines of forces are acting in the same perpendicular line and are equal and opposite in direction. With any slight inclination, the two lines of forces diverge due to a shift in the position of the center of buoyancy and a moment force will be formed between the two lines of forces. The resultant direction of this moment depends on the location of the center of gravity and a point called the metacenter.

The metacenter (usually designated as M) may be defined as the limiting intersection which is approached by the lines of action of the buoyant force and the original vertical through the center of buoyancy. This relationship is depicted in Figure 3 where GZ is the righting arm and the righting moment is the product of the weight of the vessel times the righting arm.

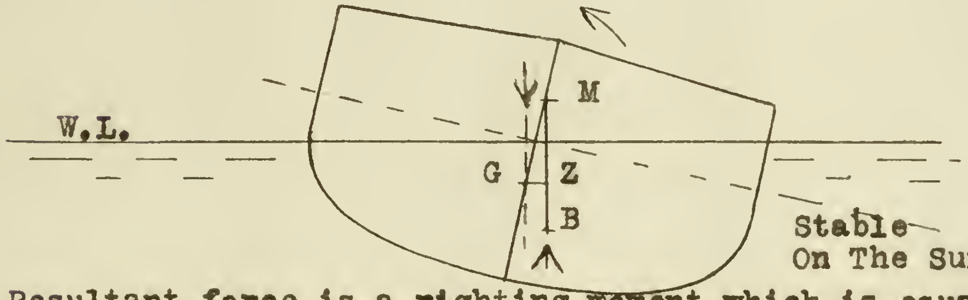
The significant point of this relationship is that a positive righting moment is provided only when the center of gravity is below the metacenter. The amount of freeboard, the relative width of the beam, the form of the hull, and other factors, which can only be properly evaluated with an experimental stability curve, effect the range of stability on the surface. A more critical situation exists during submerging operations.

Naval stydies of submarine operations show that the position of B, G, and M will vary considerably during diving and surfacing. During submergence the geometric form of the below-water hull and the center of gravity continue to change with the addition of water ballast until at complete submergence, the center of gravity will be lower than the center



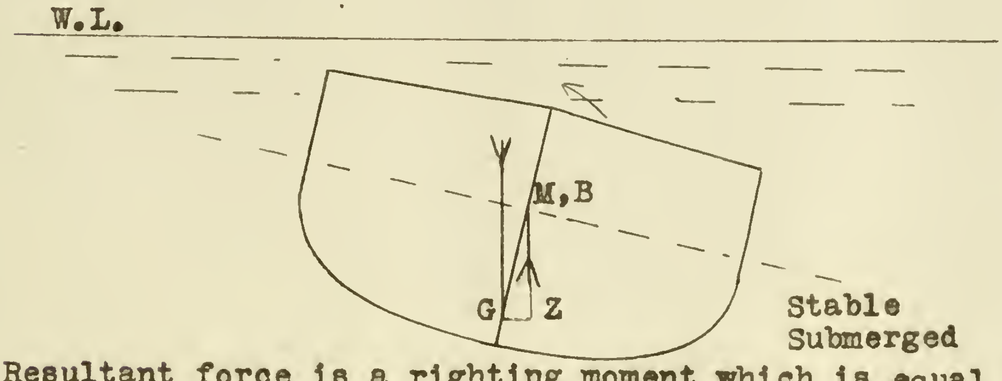
Unstable
On The Surface

Note: Resultant force is an upsetting moment which is equal to the product of the weight of the vessel times the upsetting arm (GZ), acting in the direction Z-G.



Stable
On The Surface

Note: Resultant force is a righting moment which is equal to the product of the weight of the vessel times the righting arm (GZ), acting in the direction G-Z.



Stable
Submerged

Note: Resultant force is a righting moment which is equal to the product of the weight of the vessel times the righting arm (GZ), acting in the direction G-Z.

Figure 3

of buoyancy, and the point of metacenter and the center of buoyancy will be identical. The righting arm is then equal to the distance between B - G or M - G times the sine of any angle of inclination. The righting moment is always equal to the total weight times the righting arm. The above conditions depend on a very low center of gravity as the case with a submarine. Otherwise, the center of gravity may be above the center of buoyancy in which case complete instability would result.

The critical point of stability exists during submergence when a free-surface effect is present in the flooding of the water ballast compartments. Under any expected operating conditions, it is considered virtually impossible for a free vessel to be submerged or surfaced in such a fashion that the water ballast will rise or lower perfectly horizontally. Closely controlled venting will minimize any surface motion of the liquid, but the slightest swell will cause some movement. It has been proven by naval experiments that the free-surface effects will cause the weight of the free-surface fluid to rotate about its own metacenter rather than its center of gravity and the resultant effect is that the center of gravity of the vessel will rise vertically.[21] Further, experiments have shown that this upward shift of the center of gravity in a submarine is such that a momentary negative stability can exist, even with its low center of gravity. In addition, once a vessel is below the surface of the water, the longitudinal stability is more critical to this free-surface effect than transverse stability.

The above brief discussion of stability has been presented to point out the danger to those who have or may propose the use of the "sinking one end first" method in submerging a storage vessel.[9] This

method has been used successfully in shallow water less than 30 feet deep for barges with large foundations.[5] However, it should be pointed out that these structures have been designed with a very low center of gravity, the structures never became completely submerged, and the depth of the water was such that contact was established with the bottom before the danger of capsizing occurred.

The dangers of the "sinking one end first" was apparently recognized by the Bethlehem Steel Company in their study of a submerged tank battery as reported by Mr. Lacy.[5] It is reported in this article that this method has been used for shallow water barges, but that they have abandoned this method in favor of the vertical sinking method for deeper water.

It should not be assumed from the above comments that the vertical sinking method is a "cure all" to the problem of stability during submerging operations. Upon complete submergence the water plane area (water tight freeboard) is reduced to zero and the stability becomes most critical unless the center of gravity is extremely low. The difficulty in obtaining this low center of gravity during construction is recognized and additional devices are often used to control stability during submergence.

Pontoons, fixed hull extensions, or bearing feet have been used by different designers to overcome this problem with drilling barges.[15] The Sea Engineering and Salvage, Inc. apparently recommend use of pontoons for their proposed submerged storage although the article describing this system is not clear.[4] The article[5] describing the Bethlehem system claims that no additional devices are needed in their system since the above water surface will provide sufficient water plane area. This

system does not become completely submerged as the problem would be a little different.

The exact method or device needed to control stability during submergence must be left to the prudent judgment of the designer, but it is equally important that the operator understand the problem and assure himself that adequate controls have been provided.

VII. FUEL HANDLING SYSTEM

A. Fuel Delivery

The inherent characteristics of a completely submerged internal displacement system provides a practically automatic fuel delivery system. For storage, the product would be pumped under pressure into the submerged tank displacing the sea water, or for some applications the tank may be filled prior to submergence. When delivery is required, the pressure head resulting from the difference in specific gravities of the product and water will provide an automatic method of delivery within certain limits.

The height to which the product will be pushed by the differential pressure is a function of the specific gravities of the water and the product and the depth of the water. This can be expressed by the following relationship:

$$(D)\ (.433)\ (S_w) = (D)\ (.433)\ (S_p) + (H)\ (.433)\ (S_p)$$

or

$$H = \frac{D\ (S_w - S_p)}{S_p}$$

Where:

H = height above the surface of the water in feet

D = depth of the water in feet provided tank is not located close to bottom

S_w = specific gravity of water

S_p = specific gravity of product

.433 = [illegible]

A table of some typical values of H, and the pressures at the water line, assuming a constant specific gravity of sea water of 1.020, is presented as follows:

D (ft)	API Gravity	S_p	H (ft)	Pressure (Water Line) (psig.)
50	25	.9042	6.4	2.5
	35	.8498	10	3.7
	55	.7587	17.2	5.6
	70	.7022	22.6	6.9
100	25	.9042	12.8	5.0
	35	.8498	20	7.4
	55	.7587	34.4	11.2
	70	.7022	45.2	13.8
200	25	.9042	25.6	10.0
	35	.8498	40	14.8
	55	.7587	68.8	22.6
	70	.7022	90.4	27.6

The rate of discharge of the fuel under a natural displacement system will depend on the following conditions:

1. The specific gravity of the product.
2. The height above the surface of the water to which delivery is desired.
3. The length and diameter of the delivery line.
4. The viscosity of the product.
5. The depth below the surface of the water-product contact.

With so many variables, no attempt will be made to arrive at a general conclusion. The necessity for pumps to increase the rate of discharge will depend on the above conditions and the desired rate of delivery by the operator.

[illegible]

The size and arrangement of the inlet lines and connections will vary with the intended application and the specifications of the operator but no specific problems are foreseeable.

For the offshore operator who would use a submerged storage, separate and detached from the production platform, a flexible inlet hose would lead from the production platform to the top of the storage with suitable valve connections to control the flow. A separate discharge leading to a tanker or barge mooring (moorings will be discussed separately) would be used.

The basic arrangement of fuel inlet and discharge lines would not differ for an installation which combines a production platform with a submerged storage system. The upper part of the structure which is above water would have to include facilities for treating the crude. The proposed Bethlehem Steel Company construction design includes a treating tank above water, connected to the lower storage system, for removal of the salt water, and the connections are such that both inlet and discharge lines are attached to this upper tank. It is considered that this arrangement basically should be defined as part of the production system rather than the storage system in a true submerged storage.

There are some potential applications, such as the military, in which a discharge connection to a pipeline leading to shore would be used.[9] Part of the pipeline leading to shore may be of steel or non-flexible construction. The hose connecting to the storage system, however, should be flexible and of sufficient length to provide for any lateral movement

[illegible] as the [illegible]

L. Fuel Level Indicating Systems

The need for a reliable, remote reading, fuel level indicating system is apparent. The danger of pollution due to overflow makes this requirement even more important. Several types of systems can be used, but insufficient data are available to the author to properly judge their reliability. An operator may wish to consider some of the following types.

With a known value of the depth of water and specific gravities of the water and product, a pressure gage placed at a given height above the surface in the product discharge line could be interpolated in terms of the height of the oil water interface in a displacement system.

A variation of this differential pressure method is proposed in the Sea Engineering and Salvage, Inc. design by what is called the "open cup system".[4] This is not a true level measuring device, but a level control device to prevent overflow when full. The "open cup" with a small container for ullage is placed in the production platform superstructure at a height to which a column of oil of known specific gravity would rise when the storage tank is full and is supported by sea water of known specific gravity in a known depth of water. For offshore use this would appear excellent for overflow control, but an additional device would be needed for measuring the contents when less than full.

A flow meter to measure the input and output could be used as an indirect method. The corrections for temperature changes and inherent errors in such a method would present some difficulties and the sole use

[illegible]

[illegible]
[illegible] field level
under varied cond[illegible] 2 tests and one of the
other method [illegible] safety and accuracy.

[illegible] contamination, normally is considered to be the [illegible] characteristic for storage of liquid petroleum in a [illegible] storage system. Theoretically, the density of some very low gravity crudes or products would preclude their use in a water displacement system but in the final analysis, the viscosity at the storage temperature would be the limiting factor.

The temperature [illegible] under expected operations must be considered [illegible] before a final decision is made with regard to heavy crudes or products. It is theoretically possible to install a heating system with steam lines [illegible] running through the submerged tank, but it would have a very low efficiency and add greatly to the cost of the system. Where viscosity is not a problem, but heating is required for filtration before use, the heating system should be located at a more advantageous point in the discharge system. Such would be the case for diesel oil used by the Navy in areas where the temperature is less than [illegible] degrees F.

[illegible] Emulsification.

If the crude or product is in contact with the water in a displacement system, the degree of emulsification will depend on the type of product, the amount of agitation, and the presence of any emulsifying agents.

[illegible] tank. [illegible], [illegible] agitation, the [illegible] at the highest point of the tank and probably [illegible]. Also, the inlet for the water should be below any expected [illegible] of the product. Entrance of solid matter with the water can be minimized by extending the inlet opening well [illegible] surface.

The water [illegible] some of the heavy refined products and some [illegible] will depend on the intended application and specifications of the [illegible]. The water tolerance for fuel oil for naval vessels and [illegible] jet fuel is very low and storage in contact with the water would be considered prohibited, especially for the fuel oil. The [illegible] heating oils is questioned, but it is known that [illegible] have been stored in contact with ground water in [illegible] storage. The Petroleum Engineer of August, 195[illegible] describes such a system used by Esso Standard, but the type of heating oil is not [illegible].

A submerged storage can be constructed at additional cost in a manner to prevent contact of the product and the water, yet retaining the principle of [illegible]. The [illegible] flexible bag is one method. However, since [illegible] is needed to provide weight or a means for water [illegible], the flexible bag can be installed inside a solid shell. A floating [illegible] membrane separator would be another method.

[illegible]

A [illegible] [illegible] [illegible] [illegible] may be considered an essential component of a [illegible] [illegible] [illegible] as assumed in the statement of the problem. There may be some [illegible] in the potential applications where the need would not exist at all times, but alternate use would require consideration of [illegible] [illegible].

The [illegible] [illegible] and [illegible] terminals for petroleum, where anchorage or mooring of [illegible] [illegible] the vessel is required, are well known to the military and to the [illegible], and description of these would be redundant. The difficulties in [illegible] the buoys, anchoring in the proper location, and completing the hose connections have been recognized, and several designs have been proposed recently to overcome these problems.

Several articles in [illegible] literature have described a doughnut shaped floating offshore terminal developed by the Marine Oil Terminal Company, [illegible] of New York. This forty-foot diameter buoy is anchored at the sea [illegible] [illegible] [illegible] [illegible] connections leading to shore are permanently attached. A tanker [illegible] mooring lines from its bow and is free to swing [illegible] with the wind and tides. Hose lines are picked up from the buoy by small boats and floated around to the discharge points along the tanker for connection.

The article in [illegible], by [illegible], [illegible] of the Sea Engineering and Salvage, Inc., describes a somewhat similar system except that the tanker is able to moor alongside a [illegible] anchored barge. This barge has a [illegible] [illegible] of [illegible] [illegible], and the center of gravity can be adjusted by means of [illegible] ballast.

Each of these methods of shoring systems have the characteristics which would be highly [illegible] shoring system. The type shoring which [illegible] in Table [illegible] includes the features of the [illegible] types of tunnels. Shoring as a means of [illegible], even as a protection [illegible], cannot be accepted as a [illegible]. The [illegible] can cause considerable damage to [illegible] the tunnel or the structure.

C. PROBLEMS

1. Corrosion Protection

The problems of corrosion have posed a major problem for marine vessels and offshore structures. However, it is important to note that the problems have been confined basically to the splash zone where the area is exposed alternately to the atmosphere and to the sea water. The problems relating to areas which remain submerged have been very minor.

The January [illegible] issue of *World Oil* includes several articles on the problems of corrosion in offshore structures and all agreed that corrosion in the submerged zones can be arrested practically 100 per cent by use of cathodic protection.[illegible] One article stated that the cost for protection of a complete structure (both submerged and exposed) would run about 3 cents per square foot per year for impressed current protection and about 6 cents per year for sacrificial anodes. The relative costs for a completely submerged system where no contact with the atmosphere exists would be expected to be lower. On the other hand, the operator with a combination floating and platform system will have to consider the increased costs of corrosion protection.

2. Marine Growth

The problems of marine growth are related more to a sea going vessel where the growth will reduce the speed. Anti-fouling paints used on these vessels are effective for approximately two years and at least double this period could be allowed [illegible] before any attention to a

storage [illegible] it is believed that many plant [illegible] would be [illegible] at these [illegible]. On the other hand, nozzle systems [illegible] or pipelines.[7] This would [illegible].

5. Repair or Replacement of Accessories

A greater need for [illegible] inspections of valves, hoses, connections, and [illegible] will exist for a [illegible] system than for a surface system. With the [illegible] in a ruptured hose or connection, frequent inspection [illegible], which will add to operating expenses. This will [illegible], however, [illegible] inspection is a possible solution.

[illegible]

[illegible]

[illegible]

Due to the numerous patent records and lack of any cost data, no attempt will be made to examine the various concepts of submerged storage found in the patent files for offshore operating conditions. A designer will find it necessary to check these records to prevent any infringement and a list of the generally related patents are included for this purpose. They are as follows: [illegible]; 1,202,081; 1,312,356; 1,417,[illegible]; 1,606,757; [illegible]; [illegible]; 2,059,227; 2,211,956; 2,321,976; 2,337,472; 2,371,[illegible]; [illegible]; [illegible]; 2,631,558; 2,747,774; 2,748,739; 2,487,766; 2,706,[illegible]; and [illegible].

4. Proposed Systems

Several systems were referred to in the discussion of the engineering factors. Two of these submerged systems are designed by the same company and the principle difference is size. Others include a combination storage and platform system, a [illegible] installation, and a mobile system proposed for military [illegible]. Since all of these relate primarily to offshore submerged storage and are dated within the last 12 months, each will be briefly described with projected estimated cost.

Semi-Permanent 5,000 Barrel Storage Designed by Sea Engineering and Salvage, Inc.

Basically, this can be considered as a completely submersible system designed to operate with a separate production platform and a

[illegible] produc-tion (see a [illegible]) [illegible] barrels [illegible] as de-scribed by the [illegible]

The [illegible] feet in diameter, 85 feet high, and is constructed of a [illegible] stability is provided by use of temporary [illegible] bracing when under tow. The system of the internal [illegible] is done [illegible] by con-trolled air [illegible] of a [illegible] lift to pre-vent [illegible], removable fixed ballast, and three [illegible] sinking force and resistance against lateral forces.

[illegible] flow due to hydrostatic differential through fuel hoses to a free swinging [illegible], [illegible] with an "open cup" control, are the essential features of the oil delivery and control system. The [illegible] from a separate production platform.

Economic savings of [illegible] are estimated by the author for a three-tank system when compared to construction of an elevated storage, in 60 feet of water, under [illegible] operating conditions. He assumes a barge to transport [illegible] would be required in either case. Installation cost is estimated at [illegible] per barrel for a three-tank system or [illegible] per barrel for a four-tank system.

Sea Tank Farm Proposed by Sea Engineering and Salvage, Inc.[1]

The basic principles are the same as for the smaller system with added features for tanker loading and the greater weight of tanks.

The [illegible] feet in diameter, and are rated for a capacity of [illegible] barrels. Due to size and weight, a

[illegible]

[illegible]

and consists [illegible].

The [illegible] consists of a [illegible] mooring barge with storage [illegible] oriented to sea and wind direction. The sea [illegible] allowing freedom of rotation of 30 degrees [illegible] center of gravity can be maintained by use of [illegible] in three-single caissons which can be lowered [illegible]. The barge [illegible] mooring winches and means of [illegible] this type.

The [illegible] estimates that [illegible] installation of these storage tanks, one barge, moorings, and [illegible] system could be installed, excluding any gathering system, for $0.[illegible] per barrel. If installation included a gathering system with [illegible] of platforms and lines spread out approximately [illegible] miles [illegible] the [illegible] system would approximate $0.[illegible] per barrel.

A savings of [illegible] could be estimated for a field producing 10,000 barrels per day from [illegible] platforms in the Eugene Island-Ship Shoal area, based on two [illegible], tanker loading directly from this system would [illegible] eliminate the need for any barges, and second, if the oil were [illegible] the same tanker would have to go into port and [illegible] to an East Coast refinery.

Combination Submerged Storage and Platform [illegible] Barge Proposed by Bethlehem Steel Company, [illegible], Texas

The article referred to [illegible] a description of a shallow water [illegible] in which the [illegible] is supported above the water by

a submersible tank. [illegible] is not considered to have the features of a true submerged system [illegible] the definition of this study.

The combination [illegible] feet of water) storage and platform construction [illegible] of three main parts: (1) A large square mat, cut away in the center, which has access to the sea via sea valves and is flooded when submerged. (2) Four large cylinder corner columns extending from the mat to a point [illegible] below the mean water line. These have access to the sea via the mat, and are flooded when submerged, and serve as a 30,000 barrel storage compartment for oil when the sea water is displaced through the sea valves. (3) The third component is a 12,000 barrel flat-top storage compartment supported above water height by a series of hollow [illegible] the four corner columns and cross members. The [illegible] would serve as the production platform [illegible] from this component to the submerged storage in the [illegible] the hollow supporting columns. (Note: no [illegible])

The system [illegible] displacement principle and is sunk vertically by ballasting the mat and columns with sea water. Reportedly, vertical stability [illegible] is maintained by the above water surface [illegible] structure. The mat provides surface [illegible] when [illegible], and it is noted that [illegible] to counteract the [illegible] in the case of submerged [illegible] clamp [illegible] data [illegible]

In a personal communication with the author, it was estimated that the costs for a 30,000 to 50,000 barrel installation in 60 to 100 feet of water would range between $20 and $30.00 per barrel and a larger size installation in the neighborhood of 100,000 barrels would cost between $15 and $20.00 per barrel.

Fixed Installation Proposed by Mr. Stegemeyer of Mene Grande Oil Company.[12]

This proposed design is an internal displacement system consisting of six 500,000 barrel circular tanks to be constructed on-site in Lake Maracaibo principally out of prestressed concrete sheet piles connected together over their entire length by steel interlocks. In 100 feet of water, the walls of an individual tank would consist of 168 vertical piles, 125 feet in length with steel heads and points, which are driven individually into the bottom and then connected together by the steel interlocks. The bottom of the tank is the lake bottom with a hydraulic access to the lake by a pipe leading through the walls of the tank. The walls extend from the bottom to a point about 14 feet above the surface of the water.

Six tanks are constructed together and are covered by a platform which supports production equipment, pumps, and personnel quarters. The spaces between the tanks are closed and form water ballast compartments to help overcome buoyancy of the system. Wave and wind forces are resisted by the piling.

Discharge fuel lines lead to an anchored barge loading station which will serve as the tanker terminal. Gauging of the oil level can be accomplished through the roof of the tanks since tank compartments extend above the surface of the water to the bottom of the platform.

The author states that considerable experimentation on soil characteristics, water tightness, fabrication procedures, etc., are necessary but preliminary estimates of costs would be as low as $1.43 per barrel for the 3 million barrel installation.

Mobile Offshore Submerged Storage Proposed for U. S. Army by W. C. Nickum and Sons, Seattle, Washington.[9]

This can be classified as a true internal displacement, mobile system, for theoretically it is designed to have sufficient surface stability under tow to any part of the world. This is accomplished by the use of centerline air ballast tanks on each end of the vessel and a very low designed center of gravity.

The design of this vessel is based on two unique assumptions. First, it is assumed that the vessel will act as a cargo carrier and second, it is assumed that the storage compartment will never be completely vacated to provide positive buoyancy for surfacing. These conditions necessitate a compromise between over-all weight and air ballast tanks to the extent that the vessel will not submerge with over 50% capacity of the lightest product. The rated capacity is 50,000 barrels for the heaviest product.

The sinking force is provided by filling the air ballast tanks with sea water, and the (questionable) "sinking one end first" principle of submergence is proposed. The system does not provide for any type of anchoring and the effect of potential wave forces apparently were ignored.

The inlet line for refilling would presumably lead to a buoy tanker terminal and the discharge line would connect to a pipeline leading to shore. The air venting is controlled from a separate buoy.

Metering is suggested for fuel level control; and although flow by differential pressure is anticipated, suction pumps on the beach may be needed to increase the rate.

The over-all length of the proposed vessel is 295 feet, the beam would be 50 feet, and the maximum height would be 30 feet. The design is strictly preliminary, but cost estimates would approximate $14.50 per barrel under maximum loading conditions.

XII. CORRELATION OF OFFSHORE OPERATING CONDITIONS WITH THE PRINCIPLES OF SUBMERGED STORAGE

Upon the successful completion of one or more oil producing wells from an isolated offshore drilling platform in 60 or more feet of water, the operator is immediately faced with the problem of gathering and movement of the oil to the refinery. Unlike the onshore operator, lease tanks cannot be quickly constructed and the possibility of pipelines extending out to such depths within the next decade appears very remote.[3]

Under these conditions, what does he do now? The common practice is to produce the oil directly into barges which are towed to shore by tugs when filled. A few thousand barrels have been temporarily stored on some of the larger platforms, but this is an exception. First, the platforms are not usually constructed to withstand this additional topside weight under the expected forces of wind and waves, and even after drilling equipment is removed, reserve load capacity must be available to provide for work-over operations. Second, the potential hazards from fire and explosion on an isolated sea island is a definite restraining factor from combining the storage of crude on the same platform with the well head connections, personnel quarters, etc.

This use of barge transportation from distance wells is definitely not cheap. *World Petroleum* of August, 1956 reported that costs of tug rentals alone for one company averaged 40 cents a barrel and that projected cost of rentals for barge and tug for a well 60 miles out would approximate close to $1.00 per barrel.[3]

For the operator who wishes to produce and continually move the oil to shore from a successful exploratory platform or from a field with a small allowable, there is no alternate choice but to accept the high cost of barge transportation. This is true regardless of the type storage used. This assumption is made by the Sea Engineering and Salvage, Inc. in their proposal for a small 5,700 barrel submerged storage and in their comparative cost evaluation against an elevated platform.[4]

From a far distance look at the over-all problem, the only real economic solution apparent to this author lies in accumulated storage and tanker pick-up regardless of the production rate. The tanker loading procedure is considered more economical predicated on the assumption that further transportation of the oil to a distant refinery is required by pipeline or tanker after the barge transports the crude to the nearest shore terminal. This is believed to be a reasonable assumption.

True, the above proposal includes large investments for storage and sea terminals at a time when production rates are low and it would require long intervals between economical tanker loads. However, from all reports most of the fields have fairly large potential reserves, and with increased development the production rates will increase.[26] It is believed that high investment and/or high operating costs for gathering and transportation are inevitable, and it would appear much better to invest in a potentially more economical method than to merely maintain operations under a known red-ledger system. As for the long intervals between deliveries the accumulated deliveries over any given long interval will be the same under either the present or this proposed method.

The proposal for use of tanker sea terminals in the midst of offshore oil fields can present some complications. The ever present

hazards of collision and the need for marked and prescribed navigable channels from sea to the terminal are definite considerations. To minimize the problem, the operator can locate the terminal on the seaward side of the field. However, as the number of platforms in any given area increase with many different operators involved, plus the presence of fishermen, it is evident that some unified agreement must be reached under the sponsorship of the U. S. Coast Guard whereby specified navigable channels can be marked for use of tankers in these potential operations. Since these are international waters, this is a problem which can handicap all phases of offshore operations. An attempt is being made to clarify this problem through the United Nations.[26]

The location of the storage must be carefully planned to prevent future relocation. Any operator who should by chance place his tankage on an area where future drilling may be required will be faced with a very costly situation if movement is necessary.

The problems of tanker delays due to weather can again present some costly complications. Recent research with regard to sea terminals should help to minimize the loading problems, but some delays are inevitable. This is a risk which must be accepted, but compared to the over-all cost of operations under the barge system, it is believed that there is no alternative.

Assuming that accumulated storage is the answer, the logical method for providing bulk storage would appear to be a submerged system. The larger platforms in use today would be limited to topside weights equivalent to about 10,000 barrels,[5] and all trade journals report that their construction cost approximates three million dollars. To increase

the topside weight capacity of the elevated storage without loss of stability would require structures which would make the present platforms look like miniatures and the construction cost would be astronomical. Larger barges are not the answer since frequent stoppage of production is now experienced when flowing into barges.

The use of salt dome storage has been mentioned as another possible method for offshore bulk storage,[26] but no estimates of construction costs have been observed. Core drilling to define the limits of the salt dome would be expensive, and in order to serve any extensive areas of operation the costly problem of laying pipelines would again arise. This method may be more potentially economical for a field on top of a salt dome, but the submerged storage appears to have more chances of wide application.

Continuing the supposition that submerged storage is more practical, which of the present proposed systems would appear to be more feasible for a large bulk storage? In the discussion of this question, the 5,700 barrel semi-temporary system and the mobile vessel proposed for military operations are not considered directly applicable to the problem and will be excluded.[4,9]

Each of three other systems appears to have some distinct and separate advantages and disadvantages. Due to lack of detailed information, a complete evaluation cannot be made. However, lists of some of the more obvious advantages and disadvantages are proposed as follows:

Submersible Sea Tank Farm by Sea Engineering and Salvage, Inc.[4]

Apparent Advantages:

1. More readily adaptable to operating areas where permanent production platforms already exist.

2. Cheaper than the Bethlehem system when production platforms already are available and appear slightly cheaper for a spread-out gathering system, assuming the quoted price estimate includes construction of production platforms.

3. Storage compartments are completely submerged and thus are not subject to wind and surface wave action.

4. Less subject to below water wave action since a lower vertical profile is presented.

5. Can be relocated by removal of pilings.

6. Appears more suitable for depth of water over 100 feet since storage compartment does not extend from bottom to surface.

Apparent Disadvantages or Questionable Areas:

1. Requires separate production platform and size of platforms included in cost estimate of $20.10 per barrel is unknown. These may be limited to an area merely for well head connections and may not provide operating space for oil treating facilities, personnel spaces, room for work-over rigs, etc.

2. Stability during submergence in depths of water over 100 feet is questionable since restraining buoyancy from surface appears necessary.

Mobile Combination Storage and Platform by Bethlehem Steel Company.[5]

Apparent Advantages:

1. Includes an integral production platform.

2. Possibility of modification of platform for additional drilling and work-over operations exists.

3. Appears to have greater vertical stability during submerging and surfacing operations due to water plane action of vertical columns. Note that top storage would be empty during these operations.

4. Ease of mobility claimed.

Apparent Disadvantages or Questionable Areas:

1. Over-all stability of unit questionable when system full of light oil due to topside weight.

2. From a cost viewpoint, it is not readily adaptable to an area where permanent production platforms already exist.

3. Since cost estimate does not include any provisions for gathering system or tanker sea terminal, it would be more expensive than the system proposed by Sea Engineering and Salvage, Inc.

4. Subject to both wind and surface wave action.

5. Corrosions of splash zones harder to control.

Fixed Installation of the Type Proposed for Lake Maracaibo.[12]

Apparent Advantages:

1. Estimated cost appears very low.

2. Contains an integral production platform.

Apparent Disadvantages or Questionable Areas:

1. Proposed method of fabrication of piles and construction requires preliminary experimentation.

2. Would require considerable period of ideal weather for construction.

3. Oil tightness of concrete walls questionable.

4. No mobility.

5. Subject to both wind and surface wave action.

6. Subject to deterioration by marine borings.

Due to the many variables and lack of detailed information regarding the three systems, it would be imprudent to attempt to select the ideal system of the three for any given operator. However, the relative importance of production platforms to the three systems is noted and a few remarks to this point will be made.

Rather than discuss production platforms in terms of any given typical situation, some over-all statistics included in the Special Report of February 22, 1957 issue of Petroleum Week will be used to bring the over-all problem into focus.[2] This article states that mobile platforms will drill about 85% of the exploratory wells in 1957 and 1958, but the ratio will drop to about 66% by 1960. As for development drilling, it is reported that mobile platforms will only drill about 5% in 1957 and this ratio will continue to drop. From these statistics, it can be seen that the operators prefer to drill development wells from fixed type platforms which can readily be adopted to production requirements after the drilling operation is completed.

Of the two basic types of submerged storage systems - with integral platform or without integral platform - the question appears to resolve itself into whether development drilling can be accomplished from a combined storage and platform system. This point is highly

questionable although Mr. Lacey of Bethlehem Steel states they are considering the possibility. For these reasons and in the light of the estimated costs, plus some of the advantages previously discussed, it is believed that a system with the general features of one proposed by Sea Engineering and Salvage, Inc., will find the most applications in offshore production.

XIII. SUMMARY AND CONCLUSIONS

The purpose of this study has been twofold: (1) to provide qualitative criteria which can be used to evaluate a potential offshore submerged storage facility, and (2) to correlate offshore production operations with the basic concept of submerged storage and with preliminary designs which have been recently proposed.

Evaluation Criteria

Although a submerged storage system would function as a complete unit, this study has established the fact that no single criterion can be used to evaluate the potential practicability of this method of storage. To the contrary, a proper evaluation would consist of a process wherein the feasibility of a proposed type would be progressively analyzed in terms of each of the essential factors and their fundamental principles. A degree of interdependency between some of the factors is evident. However, if the analysis is approached in a logical procedure, it is believed that the individual factors can be evaluated seperately with more clarity. Such a procedure is proposed.

It is essential that the operator first establish firm operating limitations or imposed conditions before any evaluation is attempted. The variations in over-all effectiveness under different operating conditions have been demonstrated throughout this study, and if a tailored system is desired, this information must be available to the architect. A list would include the following minimum operating factors:

1. The [illegible] capacity of the system
2. The [illegible] range of gravity of the product to be stored
3. The need for an integral or a separate production platform
4. The proposed location for the system
5. The degree of mobility desired
6. The desired oil discharge rates from the storage system
7. The preference as to the type of fuel level and fuel control system

It has been established that a rigid construction, internal displacement system is the only feasible type for offshore operations. Likewise, the feasibility of a system constructed on the site is highly questionable. It is proposed that the evaluation of individual factors be made on the following:

1. Weight-buoyancy relationship

Initial consideration of this factor is appropriate since it relates primarily to the basic elements of capacity and the gravity of the product. In addition, an analysis of other factors will depend on this relationship. The following established facts are pertinent to evaluation of this factor:

(a) The critical point in this relationship exists when the system is full of the lightest oil. At that time, the net difference between weight and buoyancy is at a minimum under submerged conditions.

(b) For either a completely submerged system or a combination platform and storage system, the combined weights of the structure, fixed ballast, and the product should be sufficient to keep the system submerged under these conditions. A more equitable balance will be

[illegible]

$$[illegible]$$

[illegible]

$$[illegible]$$

[illegible]

[illegible]

[illegible]

obtained with the combination acting, since part of the structure will be above water and the gross buoyancy force will be correspondingly decreased by the volume of the above-water structure.

(c) Where additional weight or submerging force is required in the form of loose ballast or the use of pilings, these should be evaluated in terms of expected operating conditions. Such will restrict over-all mobility and present installation difficulties. Detachable ballast will be better in a temporary system, but the use of piling is recommended for a more permanent system, especially where large lateral forces must be considered.

2. Lateral forces

Having evaluated the over-all weight-buoyancy relationship, the operator must insure himself that proper consideration has been given to the effect of lateral forces. The following facts are pertinent.

(a) The effects of currents will generally be insignificant in comparison to wind and wave effects.

(b) The forces of winds must be primarily interpreted in terms of waves generated by the winds. However, the operator who desires an integral production platform must consider this additional force against the exposed structure. These forces will range from about 20 to 62 pounds per square foot for a 125-mph wind depending on the shape of the exposed structure.

(c) Wave effects will be the most important factor in lateral forces, with the inertial wave force predominating. The magnitude of wave forces is greatest in shallow water and near the surface in deeper waters. It will also vary with the shape and size of the underwater

structure. The proposed location for the system with the probability of occurrence of worst conditions is another important consideration. For equal capacity systems in a given location, the wave forces against a completely submerged storage will be smaller than those against a combination system since the combination system will present a greater vertical profile and will extend upward through the area where the magnitude of wave forces is the greatest.

(d) The method for resisting movement due to lateral forces will depend on the over-all weight-buoyancy relationship, the magnitude of expected lateral forces, and soil characteristics. A surplus sinking force under maximum buoyancy conditions will help to resist lateral forces, especially for a system with a large foundation and grid openings as opposed to a solid bottom hull. For mobile or temporary installations, additional devices may include use of anchors. Pontoons which are pressed against the bottom by hydraulic or air jacks also may be used and jetting the structure into a mud bottom will provide some resistance. In a more permanent system, pilings driven through templates are considered more practical. The efficiency of any of the above methods will depend on the soil characteristics, and the hull must be sufficiently supported to withstand distortion. In any case, the prudent operator should require evidence that the above factors have been carefully considered and that the proposed system will resist the potential lateral forces.

3. Soil bearing capacity

Soil bearing characteristics can vary widely, even in the same general area. This is primarily an installation problem, but the system must be adaptable to the various conditions. If a safe bearing

surface is present near the bottom, setting to this surface can be accomplished. However, in any case, piling may be required to prevent the system from sinking. The slope of the shelf should also be considered to prevent distortion.

4. Stability

It may be argued that stability should receive first consideration. The vital importance of this factor is not denied, but it depends primarily on the over-all weight-buoyancy relationship. The following facts are pertinent to the evaluation of this factor:

(a) Surface stability depends on the relationship between the center of gravity, the center of buoyancy, the position of the metacenter, the width of the beam, and the amount of freeboard. Although the center of gravity must always be below the position of the metacenter for positive stability, the maximum angle of inclination at which a positive righting moment exists is a better indication of stability. This information can only be determined by a model basin test project and there is no substitute. Stability can be increased by lowering the center of gravity or adding surface pontoons or air ballast compartments, but to insure adequate stability, it is imperative that the operator insist on stability curves obtained from test models.

(b) The most critical point in stability occurs during submerging operations, and it is greatly affected by presence of free-surface water. The vertical sinking method is considered to be more safe for water depths over 30 feet in lieu of the "sinking one end first" method. The combination storage and platform system will have more stability during sinking due to the above-water plane surface, but pontoon buoyancy can be added for the completely submersible type. Again, however,

the need for a stability curve is essential.

5. Fuel handling system

Whereas the previous factors have dealt with basic characteristics, the fuel handling system can be considered as a group of auxillary units. In its entirety, it will include all valves, connections, hoses, pumps, and a system for mooring the tanker or barge to which the oil will be discharged. Although the importance of these units to successful operations cannot be overlooked, they will not directly influence the choice of a type of system since they can be readily adopted to most any type of submerged system. They can be evaluated with due consideration to the following questions:

(a) Can the proposed fuel system be readily adopted to present or proposed gathering system?

(b) Have devices been provided for fuel level indication and do these devices provide for automatic methods to prevent overflow and pollution of the waters?

(c) Does the system provide for sufficient pumping capacity for discharge to tankers or barges?

(d) What are the limitations of the proposed sea terminal under weather conditions and does it have facilities for handling different size tankers or barges?

6. Cost element

When evaluating bids from two or more reputable companies the element of cost could be decisive. On the other hand, it could be very misleading and this study has proved conclusively that no evaluation should be attempted on cost alone. With the many variables which can effect the ultimate design, it is the opinion of the author that cost

should be considered only after the above five major engineering criteria have been satisfied.

Submerged Storage Correlated With Offshore Operating Conditions.

From the statistics and operating data available to the author, it is considered that the most potentially economical method for gathering and movement of offshore oil from wells outside the 10 fathom curve lies in the use of large submerged storage systems combined with tanker sea terminals. Further, it is believed that a system similar to the one proposed by the Sea Engineering and Salvage, Inc. will find the most applications in offshore production operations.

All offshore operations outside the three mile limit are in international waters. It is evident that the problems of navigation for both barges and tankers will increase as the development of this area continues. Efforts to clarify this situation through the United Nations should be continued and additional unified action, under the sponsorship of the U. S. Coast Guard, is needed to prescribe navigable channels through the offshore oil fields.

Conclusions

The potential value of a submerged storage facility to offshore operations has been established in this study, and the reports in recent trade journals suggest that some consideration is being given to this method of storage. However, as pointed out in the introduction, no overall evaluation has so far been made of the factors which can influence the design and operation of this type of storage.

In this thesis the various factors which must be considered in planning and operating a submerged storage facility have been presented and qualitatively evaluated. The basic steps of project analysis desirable

in planning a submerged storage facility have also been outlined.

The comprehensive nature of this subject is realized by the author and it is not intended to imply that all of the factors have been covered in sufficient detail. More quantitative analysis and summaries in the form of curves would have helped to clarify several factors, but the time available for this study did not permit their preparation. The timing of this study is believed to be appropriate and it is hoped that it will provide a sound basis for evaluating a potential submerged storage system to those who may wish to consider this type of storage.

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Factors influencing the
design and operation of
potential offshore sub-
merged storage facilities

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