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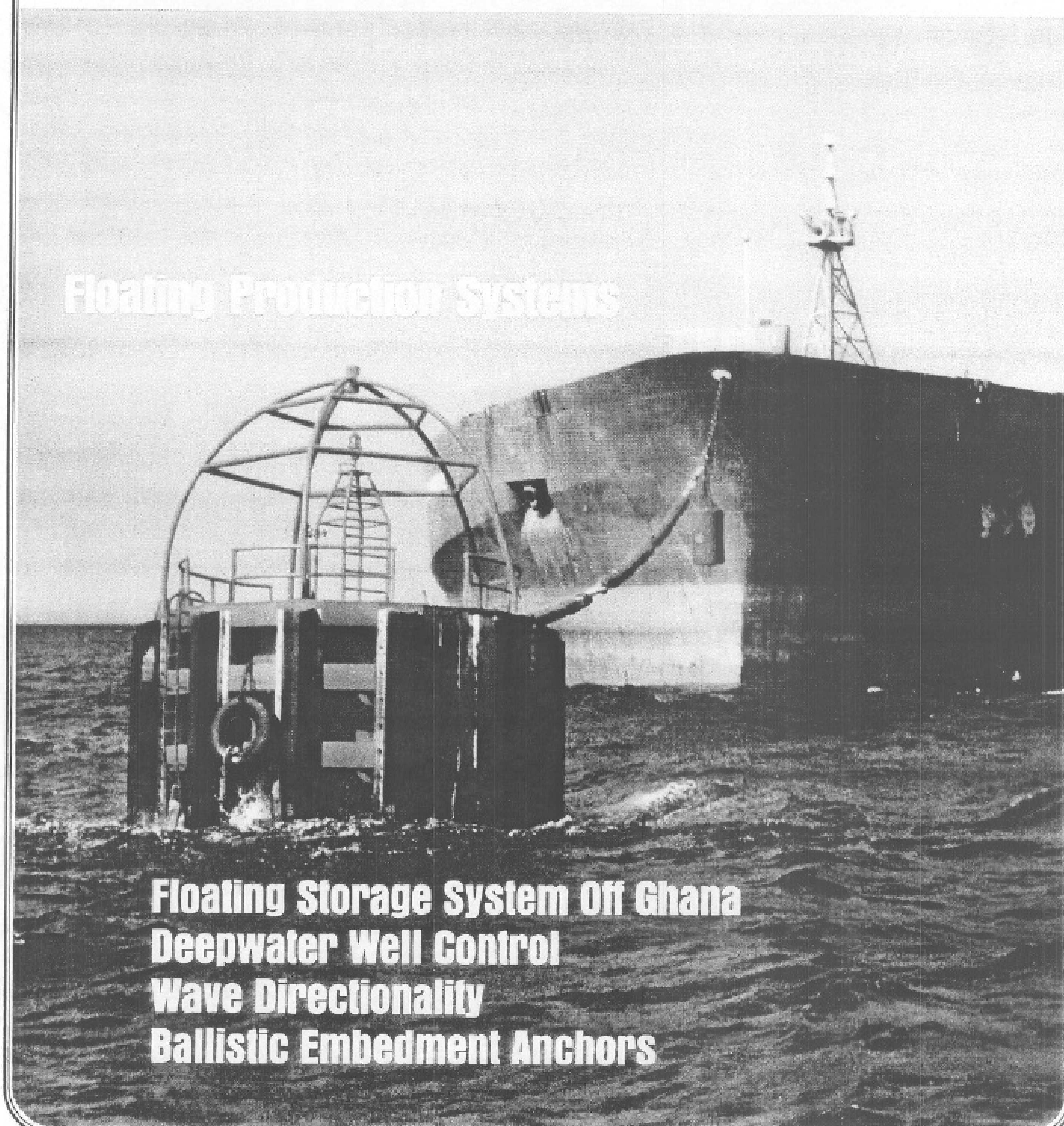
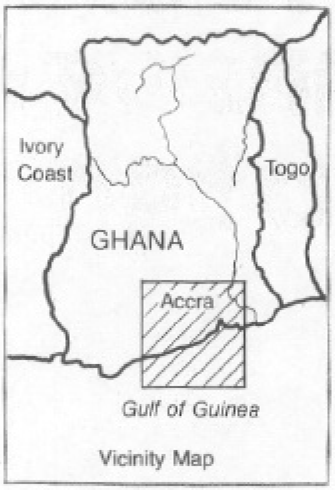
Ocean Resources Engineering



Floating Production Systems

Floating Storage System Off Ghana
Deepwater Well Control
Wave Directionality
Ballistic Embedment Anchors

Technology of the marine environment for engineering/operating men



Vicinity Map

Float System Helps Develop Marginal Field

by R. H. Gruy, *Vice President* and W. L. Kiely,
Executive Vice President, SOFEC, Inc., Houston, Tex.

Developing a small (6-9 million bbl) oilfield off the coast of Ghana, West Africa, by Agri-Petco of Ghana, Inc., was feasible with use of the Floating Offshore Attended Terminal (FLOAT) concept. Six wells have been drilled, all expected to produce about 1000 b/d each.

A Single Point Mooring (SPM) terminal provides a *permanent* mooring for a storage tanker. The storage tanker is offloaded periodically into a shuttle tanker which moors alongside. The FLOAT System thus replaces the requirement for a pipeline and shore terminal and, in this case, helped reduce cost, accelerate production start-up and allow a reasonable return on the project.

Primary advantage of the SPM terminal approach in this application is its ability to allow continuing production operations in rough weather. Since the tanker is moored by its bowlines only, it can swing freely about the mooring (weather vane) and stay bow-on to the prevailing weather. This diminishes response motions of the tanker, reducing forces imposed on the mooring system, and the storage vessel remains securely on the mooring without interruptions in production.

The SPM selected for this project is the Single Anchor Leg Mooring (SALM) design (Fig. 1). The SALM is characterized primarily by its single, constantly tensioned anchor leg and by the complete segregation of the mooring and cargo-loading functions (i.e., the loading hoses are not attached to the buoy; the buoy is a mooring device only).

Other features of the shallow water SALM are (1) the fluid swivel near the seafloor well below the keel of the maximum design tanker and (2) the compact seafloor foundation to which the fluid swivel is attached. The SALM design as a permanent mooring system offers several advantages over the traditional Catenary Anchor Leg Mooring (CALM), particularly in the areas of safety and maintenance:

The SALM is largely invulnerable to damage by tanker collision because critical components are below the tanker's keel. Also, since the SALM has no radially extending anchor chains, the tanker can approach and "kiss" the buoy without fouling the mooring.

The features are advantageous in the case of a permanent mooring as the tanker will tend to "ride up" on the buoy during certain instances of slack weather and tide changes. With no radial chains, the SALM presents a minimal obstacle to the "shuttle" tanker during offloading operations.

With respect to maintenance, a primary "consumable" with SPM's is the loading hose system. The SALM design reduces hose failures because it uncouples the hose system from the buoy thus eliminating forces that would otherwise be transferred into the hoses through buoy motions.

Other maintenance items usually associated with CALM-type SPM's are anchor-chain retensioning and periodic turntable lubrication. The SALM *never* requires chain retensioning, there is no turntable and the fluid swivel is a sealed unit that does not require periodic lubrication.

The SALM for this particular job was designed to provide a safe and reliable mooring station for the permanent storage vessel under the following conditions:

Design criteria: Water depth - 79 ft to 86 ft; Tanker Size - 64,000 dwt; significant wave height (design) - 10 ft; wind velocity (design) - 30 mph; current velocity (design) - 1.4 kt; maximum wave height w/tanker moored - 25 ft; maximum wind velocity - 40 mph; maximum current velocity - 2 kt (perpendicular to waves).

The design conditions contain small probabilities of exceedance; 10 ft significant wave will be exceeded 3% of time, 30 mph wind will be exceeded 2.5% of time and 1.4 kt current will be exceeded 1% of time. The maximum conditions are not expected to be exceeded for a 20-year recurring storm.

Design parameters: Bow hawser force (design) - 130 short tons; anchor leg force - 192 short tons; anchor leg deflection (angle w/vertical) - 36 deg; ultimate hawser force - 242 short tons; ultimate anchor leg force - 284 short tons; ultimate anchor leg deflection - 43 deg.

Design procedure: The primary design philosophy for an SPM terminal is to provide a mooring having sufficient elasticity to minimize mooring forces while retaining adequate stiffness to control the motions of the tanker. The overall SALM elasticity is the elasticity of hawser acting in series with the force—deflection characteristics of the buoy-anchor leg system.

The characteristic elasticity curve for the SALM described here is shown in Fig. 2. Static relationships between buoy net buoyancy, hawser force and anchor leg force for the shallow water SALM may be perceived by the following equations (see Fig. 3):

$$PL— \left[\frac{FB}{\text{Tan } \alpha\text{-Tan } \beta}\right] \Big/ \cos \beta$$

$$FC—PL \left[\frac{\text{Cos } \beta}{\text{Sin } \gamma}\right]$$

PL—Bow hawser force
FB—Buoy net submerged buoyancy
β—Angle of hawser w/horizontal
α—Angle of anchor leg w/horizontal
γ—$90° - \alpha$
FC—Anchor leg force

Design bow hawser force was determined by an empirical technique developed through continuing model-testing programs conducted over the past 10 years. This method was developed by Exxon Research & Engineering and Exxon Production Research Co. and has been discussed by Flory & Poranski[1] and Maddox[2].

Basically, the technique allows determination of the required SPM system energy capacity as a function of tanker size and environmental conditions. This is possible because a consistent relationship has been shown by the model tests to exist between the area under the system elasticity curve up to the significant bow hawser force (the system energy) and the tanker displacement and significant wave height.

Thus, the designer assumes several buoy-hawser systems, plots their characteristic curves and determines which of these assumed systems develops the required energy capacity at the minimum significant bow hawser force level while restraining the tanker within acceptable excursion limits.

Winds and parallel currents are treated as static elements whose effects are directly superimposed onto the wave dynamic effects. While this process implies linearity which is obviously not the actual case, experience has shown that a sufficiently accurate solution may be obtained. Many designers use OCIMF[3] equations for calculating wind and current forces:

Wind force - $[1.28\ (10^{-6})\ V^2\ Ax]\ Cw$
Current force - $[1.41\ (10^{-3})\ V^2\ (\text{draft x Lpp})]\ Cx$
Force in short tons
v - Wind velocity in mph
Ax - Tanker transverse wind area including superstructure in sq ft

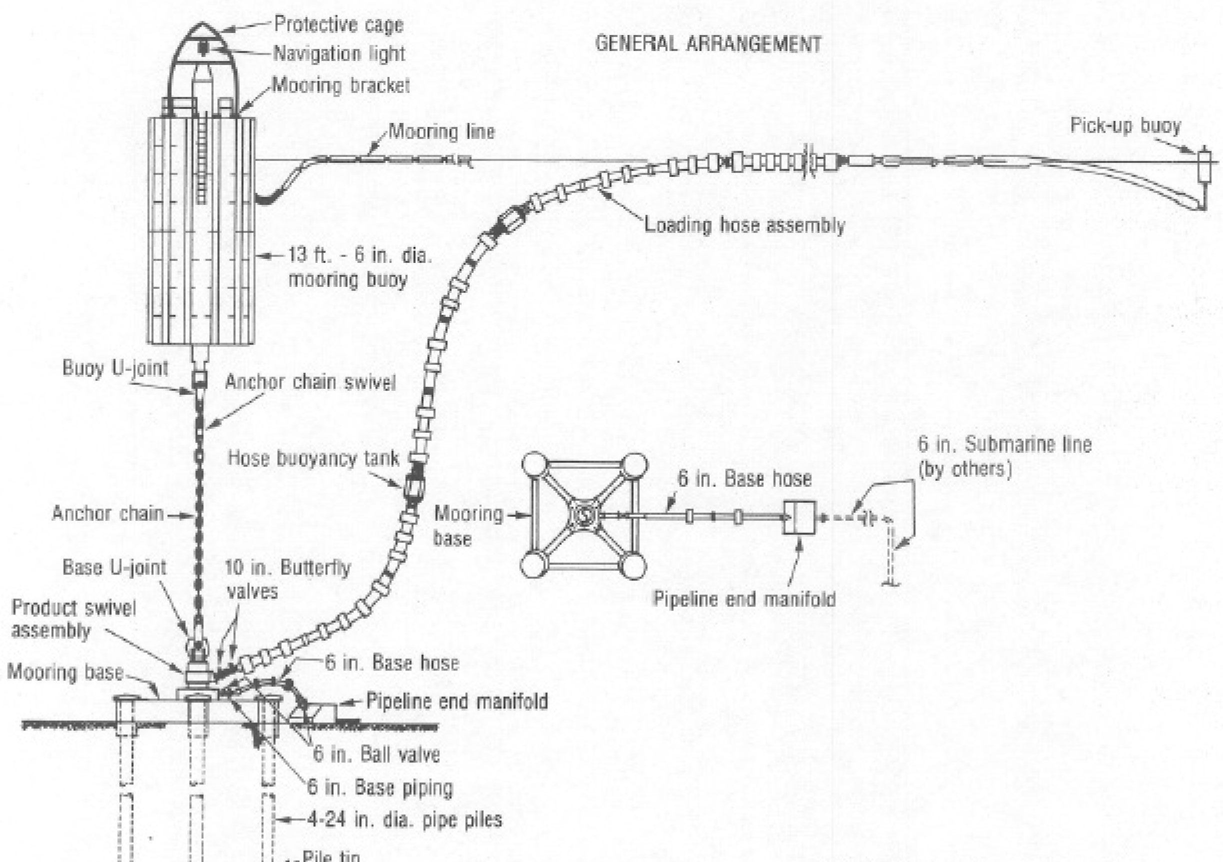


Fig. 1. General arrangement.

Cw - Bow wind force coefficient (varies from .86 for ballasted vessel to .96 for loaded vessel)
V - Current velocity in knots
Lpp - Vessel length between perpendiculars in ft
Draft in ft
Cx - Bow-on longitudinal current force
Coefficient (approx 0.1; varies somewhat with water depth/draft ratio)

Cross currents (i.e., current perpendicular to wave) in this particular instance, are treated as wave energy modifiers which may increase the effects of a given wave by causing a re-orientation of the tanker so that it assumes a quartering (rather than head-on) exposure to oncoming waves.

Their effect may be calculated by an empirical power function which was developed through the model test program or by using OCIMF data and calculating the equilibrium position of the tanker.

The design bow hawser load must be established through the application of probability data which considers a reasonable duration for the mooring system and design tanker to be exposed to the maximum design environment.

This is a judgment decision as is the selection of a realistic probability of exceedance. The designer must consider statistical environmental data together with the operational plan for the mooring system.

On the basis of the selected duration for the maximum environment and the chance of exceedance, the ratio of the maximum to significant load may be determined. This ratio, typically ranging from 1.7 - 2.5 multiplied by the significant bow hawser force yields the design force. From this force the bow hawser system is selected.

Current practice for twin-line systems recommends a design factor of 1.25 to 1.5 times design bow hawser force applied to each line and 1.67 to 2.0 on single lines or grommet-type (strop) hawsers. Once the bow hawser system is selected the ultimate loads may be determined.

SOFEC's structural design philosophy recognizes two conditions:

1. The first design condition is the hawser force and the resulting system reactions which occur when the mooring is operating with the tanker in its most critical loading condition during the selected design environment.

For a permanent mooring such as this particular application, the selected design environment is one for which there is only a very small chance of exceedance.

The selection of the design environment and of the storm duration and chance of exceedance that determines the ratio of maximum/significant load is different for a permanently occupied SPM than for an "on and off" import/export type facility.

In the latter case, the design environment may be substantially lower than the maximum predicted environment and the acceptable chance of exceedance will be somewhat larger.

Based on predicted design forces, SOFEC uses design factors on foundation and structural components of

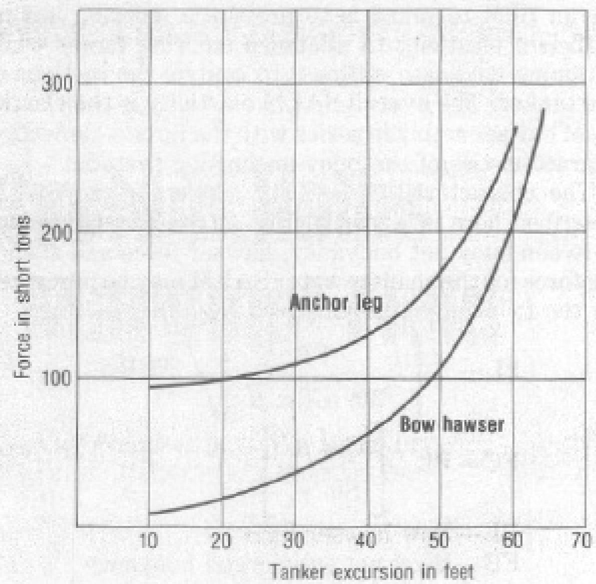


Fig. 2. Elasticity curve for SALM.

at least 2:1 and on anchor chain and chain swivel factors of 4:1 are applied.

2. Second is the ultimate load condition or the force required to *break* the hawser assembly. SOFEC applies design factors of 1.2:1 (typical) on foundation and structural components and 2:1 on anchor chain and chain swivel.

In addition to requirements dictated by the foregoing design procedures, system design must consider fabrication, transportation and installation capabilities available to complete the job. The flexibility of the SALM allows sizing of the various modular components to be compatible with lifting, transportation and installation restrictions.

Flexibility proved particularly advantageous in this case since, in order to satisfy production requirements and economics, the SALM needed to be designed and built in a minimum time frame and installed at a remote location with available construction equipment.

These requirements dictated a design which could be built at an industrialized location and transported economically to location as well as one which optimized the mooring base/piling and mooring buoy design.

Final mooring base design took into consideration the soils conditions at location (cemented sand), locally available installation capabilities (30-in. maximum diameter drilled hole) and the design loads. Additionally, criteria were placed on the design to allow the mooring base/fluid swivel assembly to be transported aboard commercial freighter and unloaded by ship's tackle onto a locally available workboat thus minimizing transportation costs.

The resultant four-pile open frame design is efficient, compact and light-weight. This design uses four each, 24-in. diam x 64-ft long piles, which are grouted into 30-in. diam holes in the seafloor. The mooring base can

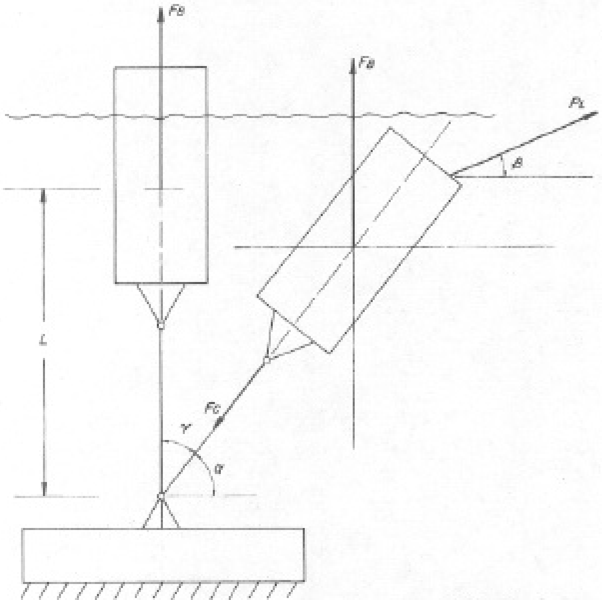


Fig. 3.

be set on location and all anchor piles secured without relocating the barge, which is necessary if installing a CALM-type mooring system.

The fluid swivel assembly permits 360-deg rotation of the loading hoses, bolts to the mooring base with 16 high strength bolts each, allowing for modular construction and field assembly. This provides an efficient means for removal when the field is depleted at a future date.

The SALM buoy is designed as a ring stiffened pressure vessel loaded by external hydrostatic pressure plus the mooring forces. It is divided into four watertight compartments by horizontal decks and is protected over its entire length with elastomeric fenders.

For this terminal it was possible to build the buoy inland, transport it by truck to port and ship it on a commercial freighter having the proper tackle to load and unload the buoy. At the delivery point the buoy was set onto the deck of a supply ship but could as easily have been placed directly into the water and towed to location.

Attachment of the mooring buoy to the base is a straight-forward operation requiring minimal support equipment. With the anchor chain and anchor swivel attached, the buoy's lower compartments are filled with water causing the buoy to rotate to an upright position and settle several feet below its design draft.

Anchor chain is swung into position over the base universal joint and connected utilizing a hydraulic connector. Ballast water is then pumped from the buoy causing the slack to be removed from the chain and the buoy to achieve the proper pretension.

The SALM is connected to the production platform by a 6-in. pipeline laid on the seafloor. The platform is a jackup drilling rig which was used to drill the wells and subsequently converted by placing pre-fabricated modular production units on the rig.

In operation, oil flows from the wells through these production facilities then directly to the 64,000-dwt storage tanker. The tanker is permanently moored to the SALM with a single 15-in. nylon mooring hawser.

Connection of the hawser to the tanker is via an oversized (to reduce the effect of chafing wear) chafing chain which attaches to a Smit Bracket at the tanker's bow. An oversized bow chock was installed on the vessel (again to reduce the effects of chafing wear) and a second Smit bracket was installed to facilitate change-out of the mooring hawser.

Oil flows to the storage tanker through a 10-in. hose coming from the fluid swivel to the surface then necking down to a 6-in. floating hose connected to a piping manifold near the bow. The manifold was constructed looking down over the side of the storage tanker.

The hose-to-manifold connection is made via a flexible ball-joint designed to reduce hose fatigue. When the storage tanker is loaded, oil is sold to transit vessels which moor alongside the storage tanker using a cylindrical fendering system. Mooring and oil transfer activities are conducted approximately every one and one-half months and require about one day to complete.

When field production declines to the economic limit, virtually all capital equipment will be salvaged for reuse. ■

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About the Authors

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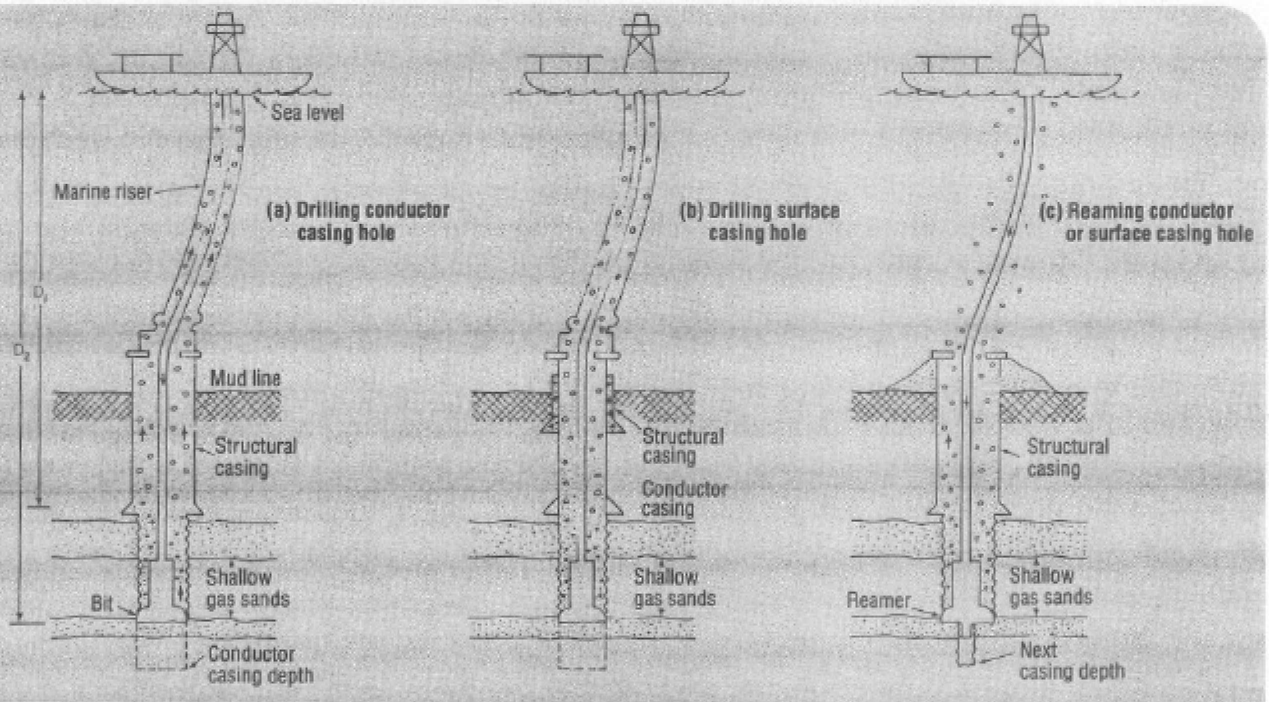

Fig. 1. Common well configurations vulnerable to shallow kicks.

Well Control Procedures For Deepwater Drilling—Part 2 Control of Shallow Kicks

by A. T. Bourgoyne, Jr., Bill R. Hise
W. R. Holden and R. S. Sullins

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In the first article of this series, criteria were presented to help decide whether to shut-in or divert a threatened blowout. This article will focus on the shallow kick situation requiring use of the diverter. – The Editors

Shallow kicks are those which occur prior to cementing surface casing in the well. Common well configurations that are vulnerable to shallow kicks are shown in Fig. 1. These situations include:

- Drilling below the structural casing string prior to setting conductor casing.
- Drilling below the conductor casing string prior to setting surface casing.
- Reaming below structural or conductor casing prior to setting the next casing string.

Structural casing usually penetrates only a few hundred feet into the sediments and conductor casing usually penetrates less than 1000 ft into the sediments.

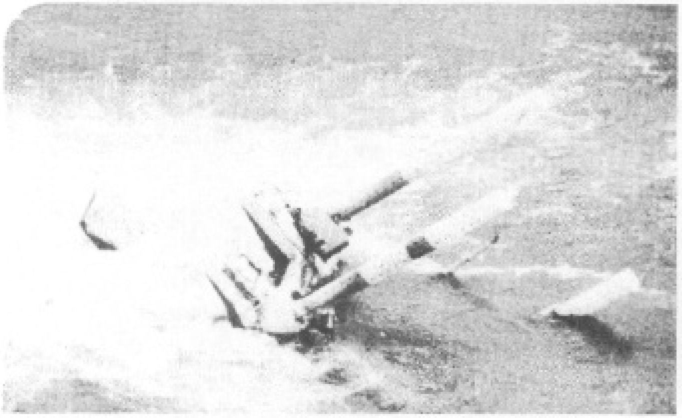
These two casing strings are usually referred to as "short" casing strings with the implication being that the safe shut-in of a kick may not be possible.

Many operators feel that shallow kicks are the worst kind, potentially more dangerous and harder to control because of the rapidity at which they can unload the well and because they usually cannot be safely stopped using the blowout preventers. Fig. 2 shows photographs of rigs lost after shut-in of shallow kicks when craters were formed beneath them.

The Santa Barbara Channel blowout in 1968 was a blowout of this type. These examples illustrate the importance of the decision of whether to shut-in or divert a threatened blowout (See Part 1; OCEAN RESOURCES ENGINEERING, April, 1978).

Shallow Kicks

Shallow well kicks, like all kicks, occur because the hydrostatic pressure at some depth in the well is allowed to fall below the pore pressure in a permeable formation at that depth. Much less reduction in hydrostatic pressure can be tolerated, however, when shallow formations are exposed without falling below the usual safety margin available.



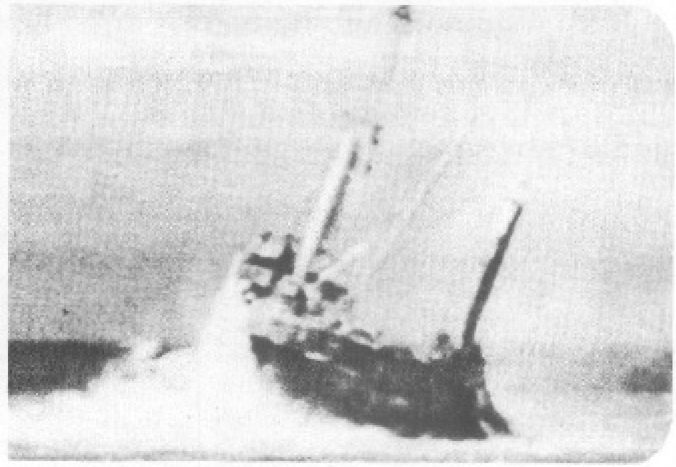


Fig. 2. Rigs lost due to crater formation after shut-in.

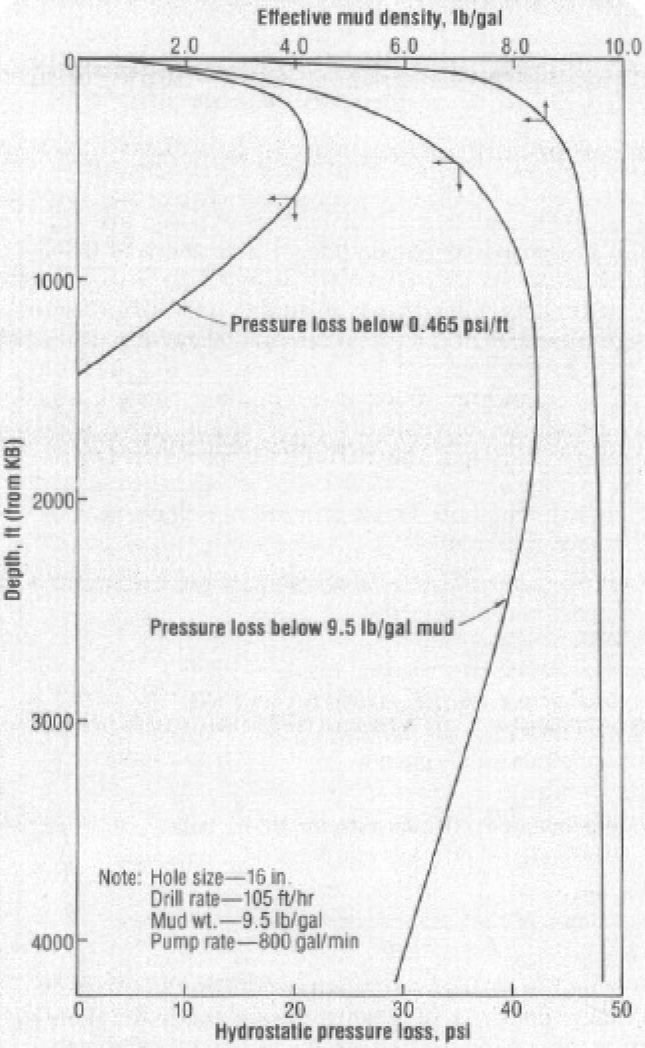


Fig. 3. Example effect of entrained drilled solids and drilled gas on effective mud density.

An excess mud density of 0.5 ppg provides a 260 psi safety margin at 10,000 ft but only 26 psi at 1000 ft. Large increases in mud density at shallow depths are not possible because of the low fracture resistance of the relatively uncompacted marine sediments.

Threatened blowout situations can be divided into those occurring while drilling and those occurring during tripping operations. Because of the difficulty in controlling a shallow kick, considerable thought should be devoted to minimizing the risk of taking a kick for both of these operations. Kick prevention is the only good well control strategy available for shallow kicks.

Kicks occurring during drilling operations result when the effective annular mud density of the circulating fluid is too low. This could happen due to either a decrease in effective annular mud density or an increase in the pore pressure gradient of the formation being drilled.

Abnormal pressure at shallow depths is unusual. However, as drilling moves into deeper water, conventional abnormal pressure due to undercompaction of sediments apparently climbs stratigraphically in the section. It can even be a problem in drilling the surface hole in some areas.

Abnormal pressures due to gas accumulations with significant vertical extent can occur anywhere. Surface casing should be set above the abnormal pressure whenever possible. Seismic data can be an aid to determine the depth of abnormal pressures in a rank wildcat. A careful study of well logs and other well data should help define the existence of abnormal pressures at shallow depths in established areas.

Many shallow blowouts attributed to abnormal pressure may actually occur because of reductions in effective annular mud density due to the presence of drilled gas in the mud. Gas cut mud is often disregarded by many drilling personnel because under normal conditions, even severe gas cutting at the surface generally will cause less than a 100 psi reduction in bottomhole pressure.

For moderate well depths, the reduction in effective annular mud density is well within the allowed safety margin. However, for exposed shallow formations, the reduction in effective annular mud density can be quite significant. Only a 52 psi loss in hydrostatic pressure at 1000 ft would cause a loss in effective mud density of 1.0 lb/gal.

Conditions favoring a shallow kick due to gas cut mud are most severe when drilling a large diameter hole at a high drilling rate with a long interval of open hole. This