The Design and Construction of Offshore Oil Drilling Outfits

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In a decade, oil drilling on the high seas has spread from fairly sheltered waters and 100-ft water depth to the very roughest areas and up to 600-ft water depth, with geological investigations already being undertaken in several thousands of feet of water.

Mobile drilling outfits are of two kinds, either relying on the sea bed for support, or floating in the water. The bottom-support units require detailed engineering investigations of the sea bed and knowledge of peak weather conditions is essential for both types. Floating outfits may be ship-shaped or semi-submersible; the latter obtain buoyancy from deeply submerged members and have limited vertical area at sea level.

The dynamic behaviour and static stability of these outfits are described and considerations relevant to design are discussed. The influence of classification societies is mentioned and constructon procedures for existing outfits are described. The essential nature of these outfits as mobile drilling platforms is stressed. Their characteristics and behaviour as floating bodies have had to be investigated by the oil industry and it is shown that modern outfits represent an entirely new concept, requiring new approaches and new operating procedures.

EXTENT OF OIL SEARCH

The search for oil and gas in the waters and seas of the world has been amply described by other writers and delivered to notable institutions and other scientific bodies by leaders of industry[1, 2]. From the early work in the inland waters of Louisiana and Venezuela, the industry moved out into coastal shallow waters in the later 1930s, following geological trends indicating the possibility of the existence of oil fields beyond the coastlines. All work off shore is more expensive than work on land and offshore development drilling of a new oilfield may be up to three times so. Thus the move was a relatively slow one, made the more cautious by ignorance of how to combat the forces of nature and the instability of some sea beds and inexperience in the design of the "carrying vehicles". An offshore drilling outfit, though an impressive structure and a very costly feat of engineering, is auxiliary to the main purpose of the industry, which is to drill for and to produce petroleum and gas, but oil-industry brains and inventiveness had to be turned to the development of such structures.

The reasons for extending the oil search to the high seas of the world, so that today men are actually drilling some 100 miles from any coastline, have been described elsewhere[3, 4]. The area of possible search is seven million square miles in the seas surrounding every coastline of the world. Well under half of this area is on the Continental Shelf and within a water depth of 200 metres.

The legal situation concerning exploration for and development of hydrocarbon reserves beyond traditional territorial limits was defined by international conference in 1958 and the Convention of the Continental Shelf came into force in June 1964, when ratification had been effected by 22 states; it is now binding upon all states. Jurisdiction over waters contiguous to a state is not necessarily limited to 200 metres water depth and a means of determining boundary lines is laid down[5].

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ENVIRONMENT

A few minutes spent pondering over a world map would give rise to the reflection that offshore drilling must involve contending with many natural problems and that these must be most varied. A mariner judges the sea bed with regard to anchor holding power. This is of great importance to offshore rigs that demand some form of anchor for restraint, but for those that use the sea bed for vertical support the nature of the soils beneath the bed, to a depth of 100 feet or more, must be studied. The characteristics, by depth, of the sub-soils typically encountered in the waters of Brunei, Qatar, Nigeria, Lake Maracaibo, the Mississippi Delta, Cook Inlet (Alaska) and the North Sea off the U.K. are shown in Fig. 1. Fig. 2 shows expectable winds and waves and Fig. 3 the water temperature and special sea-surface conditions for these same areas. There are four areas where predominantly soft sea-bed conditions are encountered and, of these, one is a relatively quiet land-locked inlet (Lake Maracaibo), two have less than violent storm occurrences (Nigeria and Borneo) and one has calm weather for the most part, but is subjected to hurricanes (the Mississippi Delta). Quite firm sea beds are encountered at Qatar, Alaska and in the North Sea, but the first named is an area with relatively few storms of any great magnitude and the last named is invariably rough and, seasonally, extremely violent, whilst ice up to six-feet thick and tidal changes of some 30 feet, with currents of 6-8 knots, occur off Alaska.

Analysis of all these conditions and the application of statistical probability of wind and wave occurrences allows one to arrive at a set of criteria to serve as governing quantities for the design of structures (see Table I). It is possible to prepare such information for any area of the world and the decision may be taken to design specifically for an area, or combination of areas, or for more world-wide use. However, one must not expect that a "universal" drilling outfit can be designed. All outfits represent the distillation of desirable features modified by circumstances, either physical or economic, and the "go-anywhere, do-anything tramp" just does not exist.

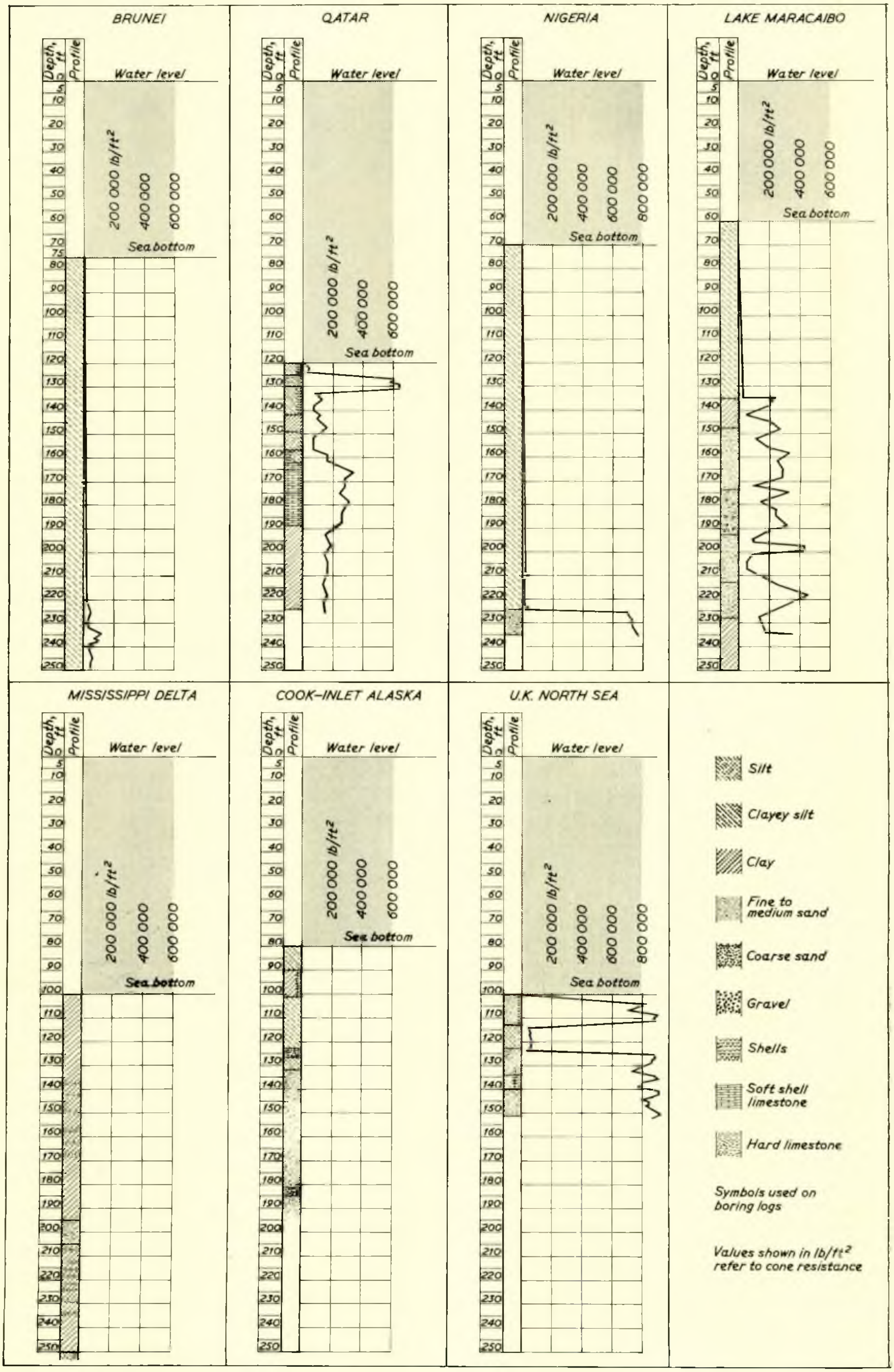

FIG. 1—*Typical sea bed conditions*

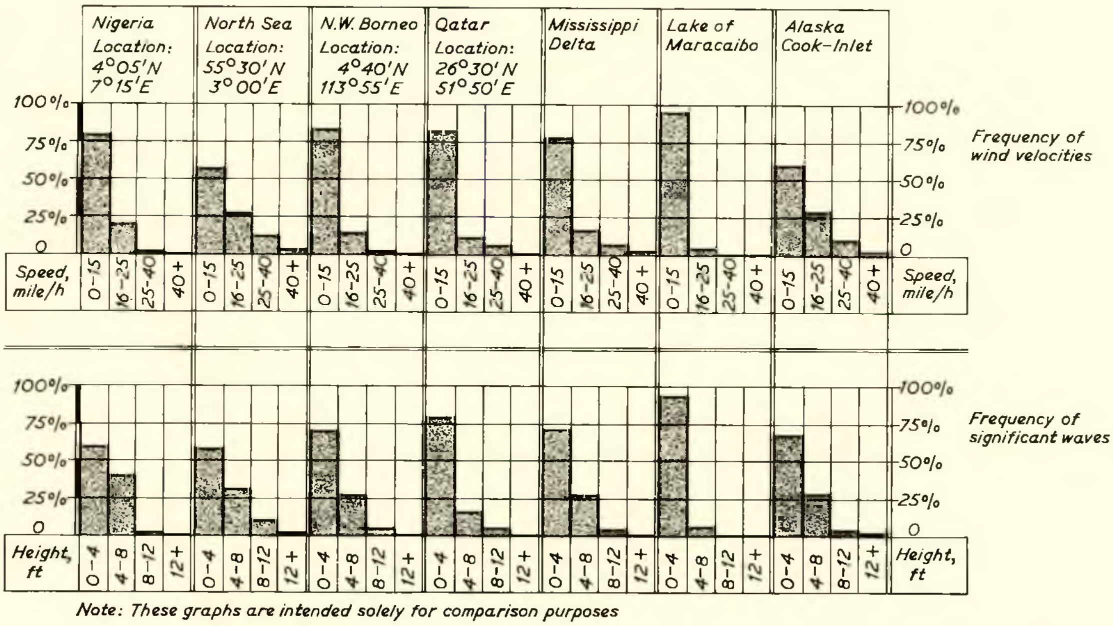

FIG. 2—*Yearly frequency percentage of wind and significant wave groups*

TABLE I—DESIGN CRITERIA

Note: These figures are intended to be indicative of criteria employed. They are not to be taken as industry standards.

Parameters	Nigeria Loc. 4°05′N 7°15′E	North Sea Loc. 55°30′N 3°00′E	N.W. Borneo Loc. 4°40′N 113°55′E	Qatar Loc. 26°30′N 51°50′E	Mississippi Delta	Lake of Maracaibo	Alaska Cook Inlet
Wave heights, ft (occurrence 1:100 year):							
maximum height in water depth of: 60–100 ft	—	winter English coast 40	—	—	—	8	—
100–200 ft	25	60	30	33	55	—	28
Winds, mile/h (occurrence 1:100 year):							
maximum gusts	90	135	100	100	180	—	100
5 min sustained	—	—	—	—	—	75	—
1 hour sustained	60	90	65	65	115	—	65
Currents, knots: maximum total current	2	3	2	2	1	1	6
Tides, ft: maximum astronomical and storm tide	10	15	10	8	11	21	32

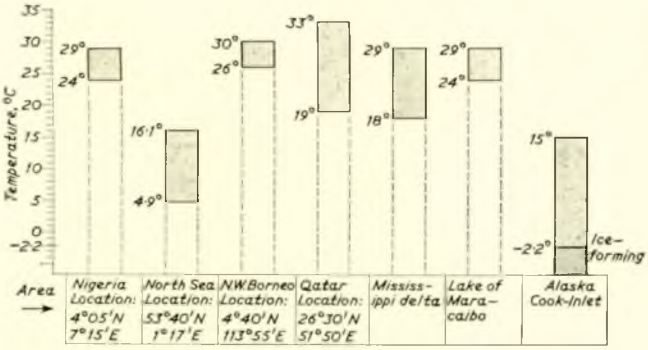

FIG. 3—*Yearly range of surface water temperatures*

DRILLING OPERATIONS

To make a very broad generalization, an oil well consists of steel pipe, between 5 inches and 9⅝ inches in diameter, cemented into a hole of between 7 inches and 12¼ inches in diameter. It is impracticable to maintain a drilled hole deeper than 3000 to 7000 ft without the insertion of steel pipe (casing), thus a deep well consists of a series of pipes of decreasing diameters in holes drilled from the base of the previous length of steel pipe. A typical 14 000-ft deep hole on the high seas in, say, 150 ft of water would consist of 200 ft of 26-in pipe embedded in the sea-bottom, 500 ft of 20-in pipe, 5000 ft of 13⅜-in, 12 000 ft of 9⅝-in and 14 000 ft of 7-in. All these "strings" of steel pipe would start from the surface where they would be connected together in forged steel housings, termed the casing head. Usually a final string of pipe of about 3 inches diameter, called tubing, is run inside the last casing string to serve to bring the oil and gas to the surface. The whole top assembly is then called the well-head, on which are mounted control valves and equipment, called the Christmas Tree. The drilling of the hole is effected by rotation of a toothed bit at the end of vertical steel shafting, the drill pipe; this, typically, is of 4½-in diameter and weighs 18 lb/ft. As drilling progresses, the drilling string is lengthened by sections of 30 ft. A heavy circulating fluid is pumped down the centre of the drill pipe; though it is commonly called "drilling mud", it is of specific and very carefully controlled characteristics and specification. Emerging at the bit, this fluid serves to clean it and then to bring the cuttings up to the surface. This fluid is also necessary to plaster the walls of the hole and keep in check, by column pressure, any gas, oil or formation water that is encountered.

The surface machinery consists of a rotary table which imparts rotation to the drill pipe, a swivel which allows high-pressure entry of mud to the rotating pipe, a derrick and hoisting machinery to handle the drill pipe in and out of the hole, for changes of bit and running of the steel casing, and large pumps for circulation of the mud. Additional control equipment, mud and hole cuttings separation devices and storage tanks, drill pipe and casing storage racks and the power plant complete the picture. This is a very scanty sketch of oil-well drilling and for proper detailed descriptions reference should be made to various published works[6, 7].

For those who would wish to acquaint themselves with the machinery and equipment and other installations placed aboard these drilling outfits, Appendix A lists that which is built into, or installed upon, the semi-submersible outfit Staflo. A general view of this outfit and the situation of the machinery is illustrated in Figs. 4, 5 and 6.

When the drilling outfit is of the type that derives bottom-support from the sea bed it is usual for the main drilling controls on the casings and around the drill pipe (6000 or 10 000 w lb/in² hydraulically-actuated valves, termed blow-out preventers) to be placed just under the drilling floor and above sea level. The outermost large-diameter conductor pipe between these controls and the sea bed is partly supported by the drilling outfit, but must be of sufficient strength to support the control valves. Sometimes it must sustain itself and the well head after the drilling outfit has moved away, in which case it is called a "free-standing" conductor or, if strengthened by steel cables, a "guyed" conductor. If the well is a producer, it is essential to provide protection and long-term support rather early, by an enclosing three or four-piled steel structure. Free-standing conductors have been used in up to 125 ft of water, and a guyed conductor in 212 ft of water.

Almost universally, with floating drilling, and certainly in water depths exceeding some 200 ft, all casing strings are terminated at the sea bottom, and the drilling controls, also, are placed there with a mass of hydraulic power lines bundled up to the surface. In order to contain the drilling mud a "marine" conductor is necessary between the top of the drilling controls and the rig floor on the drilling outfit. This conductor is given support and some restraint at the top end from the drilling outfit and may be non-buoyant, partially-buoyant, or fully-buoyant. So the situation arises (see Fig. 7) where a drilling outfit is connected to the sea bed by a slender (16-in) steel tube, inside which is the steel drilling shaft (drill pipe) and, in the case now under consideration, the drilling outfit is a moving structure, under the influence of wind, waves and current, restrained by anchor lines.

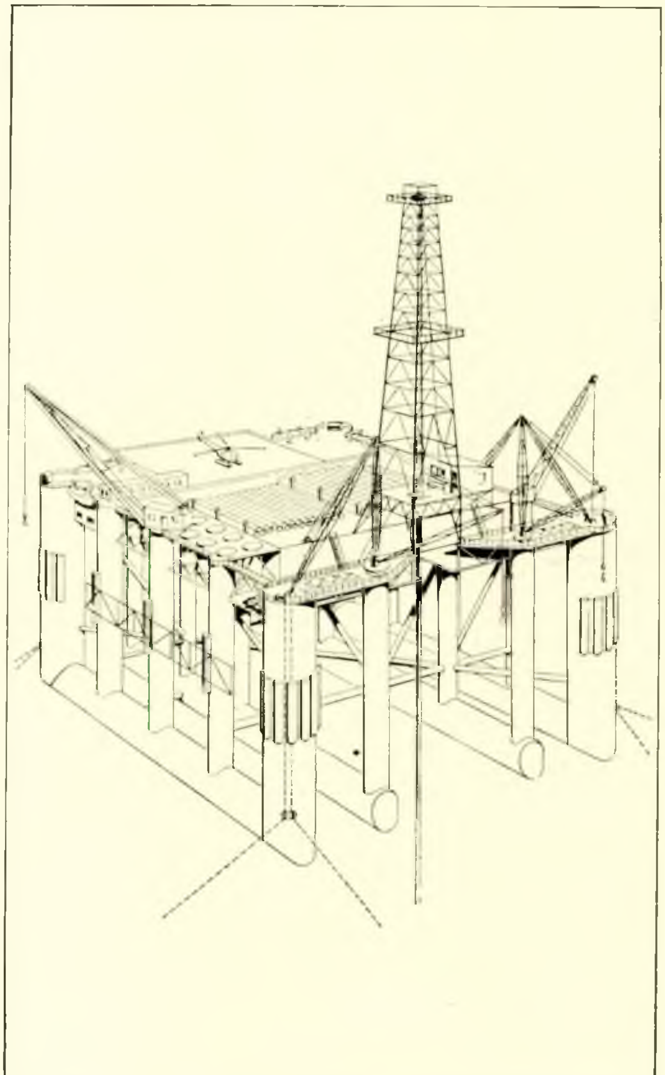

FIG. 4—*Staflo semi-submersible drilling outfit*

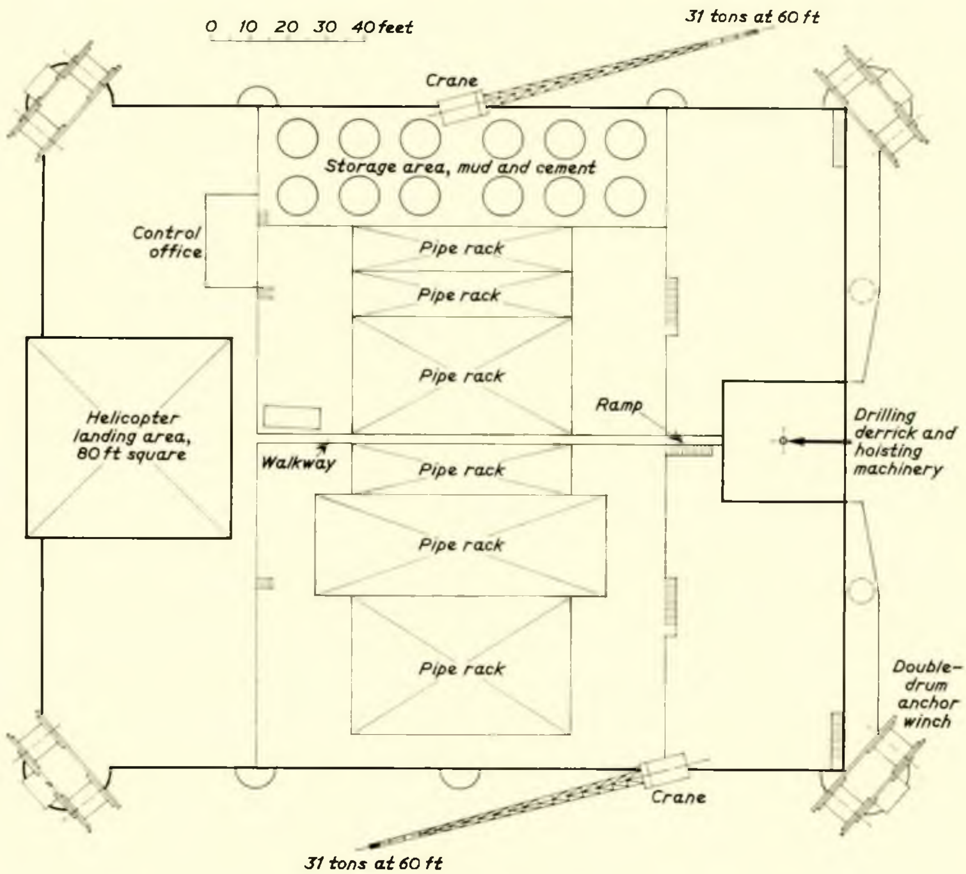

FIG. 5—*Upper deck Staflo drilling outfit*

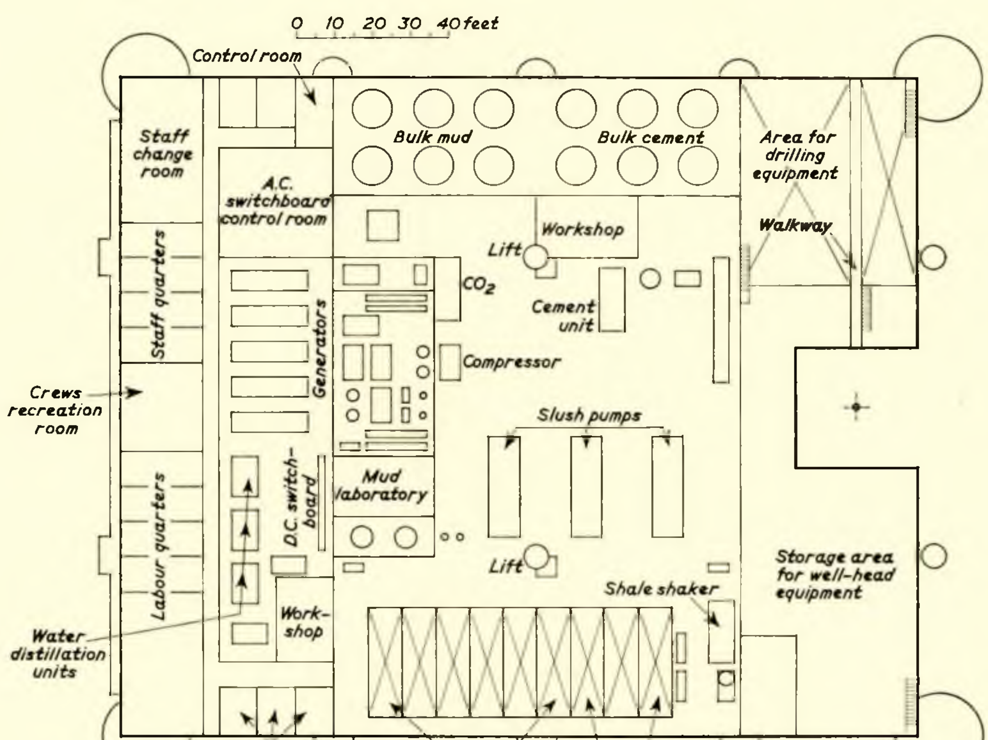

FIG. 6—*Lower deck Staflo drilling outfit*

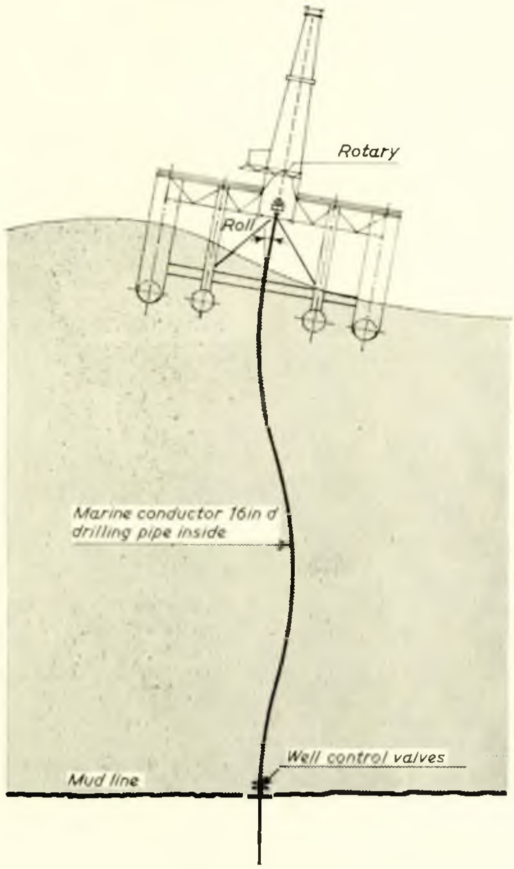

Fig. 7—*Floating outfit and pipe connexions to sea bed*

FAMILY TREE

At the present time there are not less than 20 different designs of offshore drilling outfit. Others have been built but discarded and an uncounted number of designs has been produced by the fertile brains of oil industry engineers and executives, industry consultants and, only naturally, by those quite unconnected with the business. In preparing a family tree (see Fig. 8) no account has been taken of genealogy nor historical evolution, for these matters have been dealt with elsewhere[8, 9]; neither is this illustration fully complete, it is presented as a simplified indication of the main types.

The first definite differentiation by type is between those outfits that rely on bottom-support (i.e. the sea bed) and those that employ the water itself as a means of support. Now, quite obviously, very shallow waters do not allow of the use of a floating vessel and the very deep render the employment of a bottom-supported unit economically, if not technically, impracticable. There is a water-depth range well-suited to each type, and a degree of over-lap.

In this paper considerably more attention will be paid to floating drilling outfits than those using bottom-support. This is because floating drilling, although at present a method numerically much less extensively employed, presents the greater immediate problems and will be employed on an ever-increasing scale as the oil search extends into deeper waters.

BOTTOM-SUPPORT UNITS

The bottom-support unit exists in various designs where the entire structure forms one entity. Examples of this are large barge hulls (100 ft × 200 ft) on which trussed legs or columns carrying the working decks are mounted, well above sea level; alternatively an open-work bottom grid from which rise large diameter columns, in turn carrying the working decks. Such designs are limited to some 10-80 ft of water; the lower limit being imposed by the draught of the lower hull or grid and hence the ability to float onto location and the upper limit by cost and sheer ability to manœuvre and to submerge safely. The first named when submerging, must have one end ballasted first and contact with the sea bed must be established before inducing submergence of the other end. The stability requirement for the second type also imposes a limit on water-depth, for the length and beam of a unit cannot be increased indefinitely without reaching an economic limit.

Another general type of bottom-support unit is the self-elevating barge. Here the main structure is a barge or pontoon hull, through which passes a number of support columns or legs. Typically, the hull is 140 ft × 200 ft × 20 ft, the legs 12-ft diameter, and the overall length 260 ft. In another design, the hull is triangular and the three legs of open-truss three-sided construction. In all designs the bottom portion of the legs is of a configuration and dimensions to promote or combat penetration of the sea bed and, in many cases, jetting devices are installed to assist withdrawal. The legs are lowered to the sea bed by a jacking mechanism which may be rack and pinion with electric motor drive, giving continuous jacking, or a form of tooth and bar or slot and finger with hydraulic jacks. Due to the necessity for engagement and withdrawal and vertical jacking strokes, the latter mechanisms give a discontinuous action. When the legs reach the sea bed, continued jacking causes weight to be applied to these legs as the barge hull itself is raised out of the water. Dependent upon the nature of the sea bed and on the superimposed load, the legs achieve some penetration. In areas of hard sea bottom, it can happen that very limited penetration results. This is rather unwelcome, particularly as scour may occur and also because no firm anchorage to the soil is attained; resistance to the overturning moment of wind and waves then depends largely on all-up weight of the unit. The very opposite can occur, where very deep penetration of the legs cannot be prevented, even with large diameters and additional bearing pads called doughnuts or pontoons.

Good practice dictates the provision of some form of pre-loading of the legs. This may be achieved by filling specific hull compartments with water, afterwards de-ballasted, or by applying the full weight of the hull to less than the total number of legs by continued jacking on those to be pre-loaded. Pre-loading is of very considerable importance, for it ensures an adequate leg penetration, and also the attainment of competent leg support to resist peak overturning forces.

A competent bearing layer must be sought; unless this is done, with adequate pre-loading, high loadings due to continued drilling loads and to heavy storms could cause a leg to punch through the first bearing layer, should it be too thin.

It follows from all the foregoing that self-elevating outfits should preferably have a sufficient number of legs to enable pre-loading to be performed. For other reasons, such as scour around and under one leg, an outfit should preferably be able to stand on the remainder of its legs whilst the loading on one is being adjusted.

DESIGN OF A SELF-ELEVATING OUTFIT

It will be clear from previous sections that a very definite understanding of the anticipated conditions in the area of operation is quite essential, before even broad design details may be settled. It is not practicable to evolve a universal outfit and it is usual to design the most practicable for an initial area and to modify or limit the operating parameters for the use of the outfit in another area. Perhaps the clearest explanation of this approach will be to describe an outfit intended for the U.K. offshore.

From Figs. 1, 2 and 3, the main criteria for the area are obtained. From geological expectations it is accepted that a self-elevating unit suited for some 140-ft water depth should just be adequate for the area south of latitude 54°. Thus, in this example, a year-round lowest low water springs depth of 140 ft is taken. The bottom conditions are, with some few exceptions, hard; therefore a fairly high unit-loading is allow-

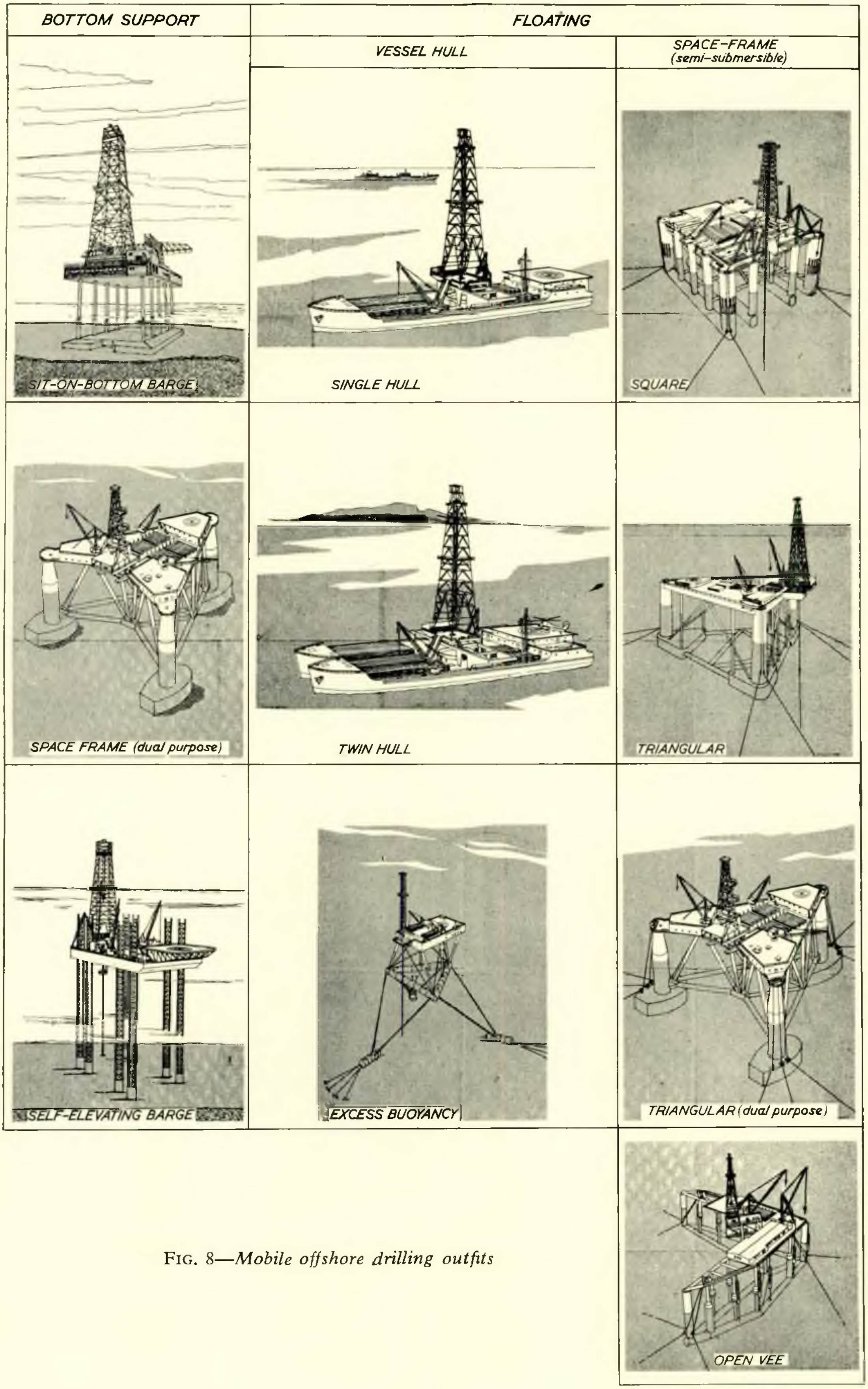

FIG. 8—*Mobile offshore drilling outfits*

able. In order to provide adequate stability on site, with means of pre-loading the legs and of re-alignment in case of scour, it is deemed that five or six legs are necessary; six will ensure proper pre-loading and also allow for retrieval of one leg at a time for any repairs. The all-up weight of a large hull and legs is likely to be 6000 tons and drilling machinery, other installations and variable load (similar to that in Appendix A) total a further 3500 tons. With six legs a diameter of 12-ft would be satisfactory, giving a fair-weather bottom-loading of 30 000 lb/ft^2 and a pre-load of some 42 000 lb/ft^2. It may well be asked why a lower unit-loading should not be chosen and the legs be of larger diameter; they need not be large diameter tubulars, which would promote too high a wave force, but could be of an open frame type construction. In one sense this is very true, but, with shifting sand ridges and occurrence of scour, which are very likely in the southern U.K. area, it is considered preferable to aim for a high loading and try to achieve some penetration of the legs into the sea bottom.

We must now advance beyond the water depth as descriptive of an outfit's capability. The legs will, even if not always, effect some penetration of the sea bottom, the sea level is affected by tidal action and also by storm build-up, and a clearance must still remain between the crest of the highest wave and the bottom of the main hull. Thus we arrive at the concept of "free spud length" (see Fig. 9). In the example, 20-ft is allowed for leg penetration, the tidal range is 12 feet, storm build-up 8 feet and maximum wave-crest plus 30 feet; with 5 feet final clearance, a required free spud length of 215 feet is arrived at. In determining the total length of the legs, the depth of the hull and the height of the jacking system must be added to the free spud length, plus some working

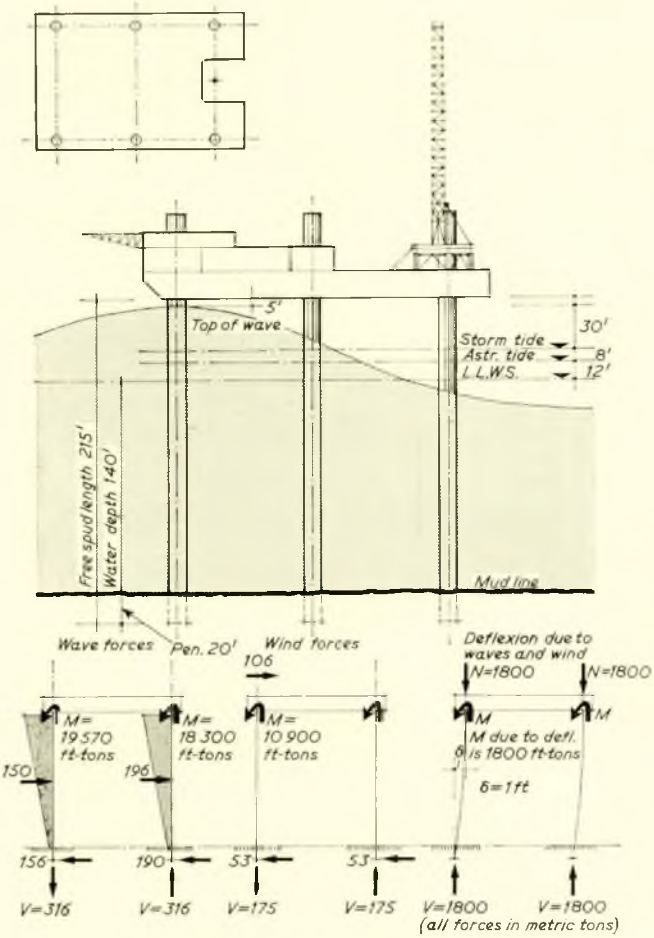

FIG. 9—*Self-elevating drilling outfit and storm forces*

margin. One last point to be considered is whether the calmer weather in summer, with reduced forces from wind and waves, would allow for a sufficient increase in free spud length on an outfit designed for maximum winter storm and thus indicate an increase in total leg length. Of course, since summer storms are of lesser magnitude, the elevation of the hull above the sea can be less, so that an outfit may be capable of its maximum summer and maximum winter free spud lengths with the same total leg length.

Some assumptions were made earlier concerning total weight of the outfit; thus some preliminary but rather firm conclusions have been necessary on overall dimensions. These are dictated by the spaces required for drilling machinery, equipment, consumables (variable load) and living quarters; also by the need to maintain adequate portal dimensions (see lower part of Fig. 9) against overturning moments. The dimensions must be controlled to keep all-up weight within reasonable bounds and to provide adequate stability whilst afloat and, of course, to keep down total volume of steel and consequent cost.

One feature of self-elevating outfits that attracts a deal of attention is the clearance, necessary or fortuitous, that exists between the legs and the vertical passage through the hull. Design clearances are determined from consideration of acceptable manufacturing and assembly tolerances, the amount needed to allow free passage, and the minimum which may be allowed as contributing to free shaking of the hull. It is general practice to provide bearing rings as far apart as possible at the bottom of the hull and top of the jacking-frame. Thus it will be apparent that a leg will take up a very slight inclination, bearing diametrically against the top and bottom rings. Sustained loading will create little problem, but gusting and wave forces do cause some shake; this is not dangerous and is not uncomfortable. It is, however, rather crude and a very recent design has arranged positive cam-operated closure plates to be held against the legs and eliminate all free play. Typically, existing outfits have in the order of one inch radial clearance on a 12-ft diameter leg, with top and bottom bearing rings of 2 ft 6 in depth. These dimensions, quite predictably, have quite recently prompted both a comment on undue free play and a carefully reasoned argument that it could never be possible to slide completed legs of some 300-ft length through the hull, and that jamming would result.

There are few rules relating to the design of these outfits. They are engineering structures, designed and analysed on the basis of accepted civil and structural engineering practices. Since they do go to sea, then applicable rules, such as those of Lloyd's Register of Shipping, are applied to the completed

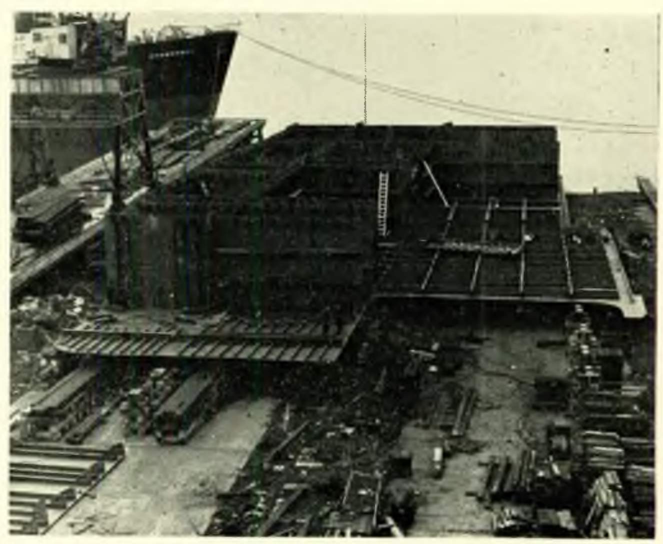

FIG. 10—*Construction of self-elevating drilling outfit*

FIG. 11—*Self-elevating outfit—Placement of leg section*

design to ensure no transgression. Where relevant, Lloyd's Register rules also are applied for the design of typical marine features, such as doors, scantlings, electrical distribution systems and auxiliary machinery. Lloyd's Register is consulted on numerous points of design, and asked by many owners to "class" the outfit. When so doing, the machinery and equipment peculiar to the drilling duty is exempted, except for scrutiny of the safety aspect.

Figs. 10 and 11 show stages in the construction of a self-elevating outfit, and show the straightforward nature of such a job fairly well. Basically the hull consists of a deck, a bottom, side-plating and bulkheads. Apart from their normal ship's function of providing compartmentization for collision safety and work space requirements, the bulkheads are also important from a strength point of view. Arranged in a pattern in accordance with the leg configuration, they form the webs of longitudinal and transverse girders, the deck and bottom being the flanges, which are the backbone for supporting all gravity loads and for providing the strength of the unit to resist horizontal loads. Particular care should be given to the design of the areas where the leg transmits large horizontal forces to the hull.

The hull should be analysed for the following loading conditions:

1) hull jacked up to drilling position and resting on all spuds; stresses caused by vertical loads (own weight, weight of machinery, equipment, drilling supplies) and by horizontal loads (wind, waves, current);
2) hull jacked up in pre-loading position and resting on less than the total number of spuds; stresses caused by vertical loads mentioned in 1); it is normally assumed that pre-loading takes place under calm weather conditions as, indeed, it should be, so that no horizontal loads need be taken into account;
3) hull floating and legs partly or fully raised; stresses caused by vertical loads listed in 1), to which weight of legs should be added, and by roll and pitch of hull and legs.

FLOATING UNITS

The most obvious manner in which to take a drilling rig to sea is to mount it on a barge or ship (the early experimenters did just that). The barge has the advantage of limited draught, which may be necessary for access to operating bases in some overseas countries where river mouths are obstructed by bars, but may have insufficient freeboard and poor stability, particularly if almost all drilling machinery and quarters are installed above the main deck. A ship can have excellent stability, very great cargo space and load-carrying ability, and machinery and quarters may be installed in the most advantageous manner. Both of these types represent very well-known constructions, served by generations of experience and detailed classification rules. They may be built almost anywhere, with no dearth of competent yards. They can be slipped for inspection and repair, and tow is relatively easy over long distances. Their very background or genesis makes the provision of self-propulsion simple. Existing hulls may be used for conversion to drilling duties and this is very popular[10], though purpose-built vessels of original design are also appearing. When the barge concept is developed, with greater freeboard, shaped bow and stern and, perhaps, an intermediate deck, it becomes difficult to determine the point at which it becomes a ship or vessel.

Referring once again to the primary purpose of these offshore outfits—to drill wells—a very important matter is their behaviour as support platforms. A barge or ship is essentially rather "lively" in wind and weather, the more particularly when constrained at a location and unable to orient to meet oncoming seas in the most advantageous manner. Therefore attention has been directed to an improvement (reduction) in this liveliness. Three methods have been adopted, sponsons, outriggers and twin hulls. Not a great deal has been done with the first-named, but reasonably successful examples exist of the other two. It is thought unlikely that the outrigger design will be repeated, for the dynamic behaviour has not been completely satisfactory. The twin-hulled approach has been quite successful and motions of the working floor show substantial improvement over single-hull designs. The total carrying capacity of this design is huge, and all drilling machinery, auxiliary equipment and quarters are most comfortably disposed.

Whilst reviewing this type of outfit, it should be remarked that on all vessel-type drilling units the drill-pipe driving unit is mounted on gimbals to reduce the bending moment in the drilling shaft (drill pipe) occasioned by roll and pitch. The twin hulls and the gimbal mounted table remind the author of unusual vessels constructed in the 1870s for the cross-channel passenger service[11]. The first was *Castalia* of 1533 gross tons built in 1874; she consisted of two half-hulls with a gap between, firmly bridged by a massive platform. The second was *Bessemer,* a single-hull provided with a suspended and pivoted saloon, intended to move in two axes to combat the rolling and pitching of the vessel; gyroscopic stabilizing was planned, but, as built, the saloon was provided with hydraulic rams, the control of which was to be effected by an operator watching a spirit level. The third vessel was another attempt at a twin-hull *Calais-Douvres,* this consisted of two double-ended hulls, bridged strongly, and with one large paddle-wheel in the gap. This digression has little to do with floating drilling outfits, but does illustrate the delights of browsing through earlier engineering developments and perhaps also indicates that such research can be rewarding; the author therefore craves indulgence for this paragraph.

Experience thus far is that all ship-shaped vessels, regardless of modification or auxiliary devices, fall short of the all-weather performance of the semi-submersible class of drilling outfit and it is this type of design which is securing ready and rapid acceptance in the industry, above all for the rougher-weather areas.

The semi-submersible, column-stabilized outfit (Fig. 5) is a logical development from the bottom-support space-frame structure; indeed, the very first semi-submersible, *Bluewater I*[9] was derived from the Kerr-McGee No. 46 bottom-support unit. This class of outfit is characterized by a very substantial beam, large freeboard, and limited vertical area presented to wave action at sea-level. The lower hull consists of a tubular grid structure, or several large "torpedoes", from which rise support columns to the upper deck. The corner columns are very large and provide stability. These outfits exhibit very excellent dynamic behaviour and thus provide a remarkably stable drilling platform. Against this they have rather limited live-load capacity, a high centre of gravity because there is virtually no cargo space whatsoever below the main deck, present a large area to winds and, in general, are rather sensitive to changes in weight and weight distribution.

This question of outfit stability will now be discussed with more detail under the two aspects of "dynamic behaviour" and "static" stability.

DYNAMIC BEHAVIOUR

It has been shown in Fig. 7 that the drill pipe and surrounding marine conductor are bent and distorted by the movements of the drilling platform. Permanent distortion must be avoided and, to stay within acceptable stress levels, a limit to movement must be imposed in some manner. The six degrees of movement of a body are shown in Fig. 12.

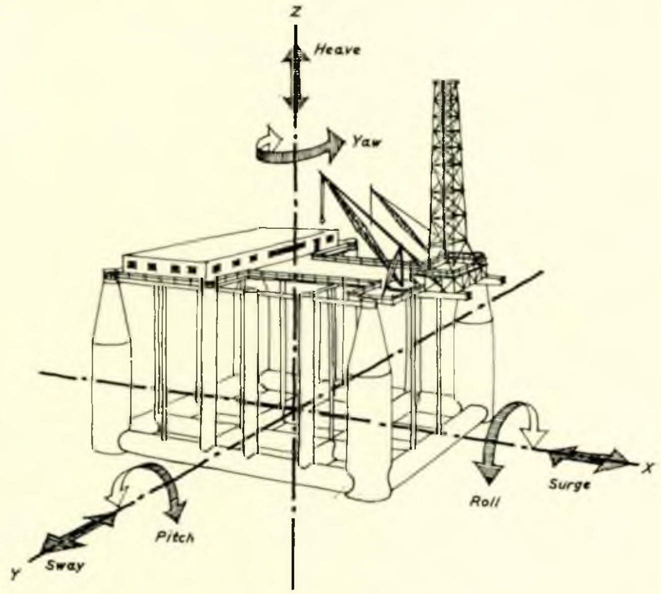

FIG. 12—*Six degrees of movement of a floating drilling outfit*

It is important to appreciate that no mooring system can accomplish any significant control over the magnitude of short period oscillatory surging or sway. Floating objects tend to move with the water particle velocities and the body to be moored should, therefore, have a concentration of mass in the zones where the water particles exhibit smaller orbits. For this reason the semi-submersible is superior in dynamic behaviour to the vessel. The effect of the mooring lines is on the fixed displacement associated with the constant components of the wind, and current forces. The forces associated with the fixed displacement are in the order of 10 per cent of the maximum wave force; these former are counteracted by the mooring lines and dictate, to a large extent, the mid-point of the oscillatory surge and sway. The stiffer the mooring system, then the more nearly the centre of movement can be held to the centre of the mooring system (a vertical line from the sea-bottom well-head). However, if sufficient scope is not allowed, the lines will become taut and fail, or move the anchors. The short-term oscillatory forces far exceed the capacity of any conceivable mooring system and there must be sufficient flexibility to allow for these motions. Too rigid a mooring system could also bring the system into a condition of resonance with the waves and large build-ups in force amplitudes would result. Thus, apart from arranging the platform configurations, submergence and mass concentration to achieve the lowest practicable oscillatory motions, we must then learn to live with them.

The factors contributing to bending of the drill pipe and conductor are the horizontal movement of the platform, and the pitch and roll. From analytical studies of the whole set-up indications of allowable platform movements have evolved. It is unnecessary to go into the matter in any detail for this presentation and it should suffice to say that a rule-of-thumb allowance for total platform movement is 5 per cent of the water depth. Thus, for deep-well drilling in 600 ft of water some 30-ft displacement from centre can be allowed. How well do existing designs meet this need? There is no easy answer, but the maximum sea conditions can be indicated in which drilling operations may proceed and above which work must cease, with the outfit continuing to exist in the roughest weather, relying on the anchoring and holding station on the well site. Before discussing these matters, the degree of heave of the outfit should be mentioned. This expresses itself in involuntary lifting of the drill pipe and is overcome by the provision, in the drill-string, of sliding joints. These typically have a range of five feet of movement and as many as four have been used.

The performances of a ship-shaped drilling vessel and a semi-submersible drilling outfit in respect of surge, pitch, and heave, as determined from model tests are given in Fig. 13.

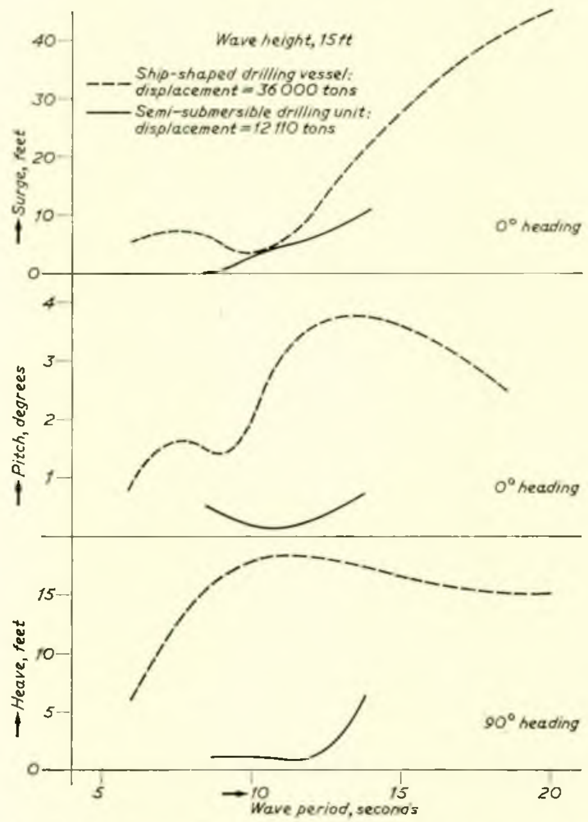

FIG. 13—*Dynamic behaviour of floating drilling outfits*

These particular movements and the heading of the 15 ft waves show large movements of the ship-shaped platform. The author readily concedes that a study of platform movements demands many series of model tests, with varied headings and also that ship-shaped vessels may be oriented in regard to prevailing weather in any area and the most comfortable position chosen. Broadly speaking, orientation of a semi-submersible is of no great consequence, for length and beam dimensions are nearly equal. What is clear from the illustration is that movement of the ship-shaped platform will require the shutdown

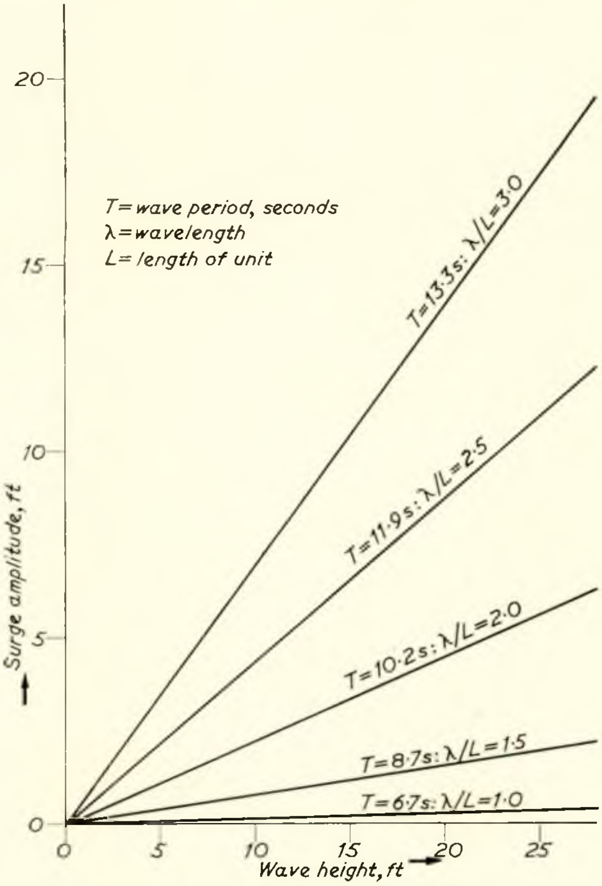

FIG. 14—*Surge motion of semi-submersible*

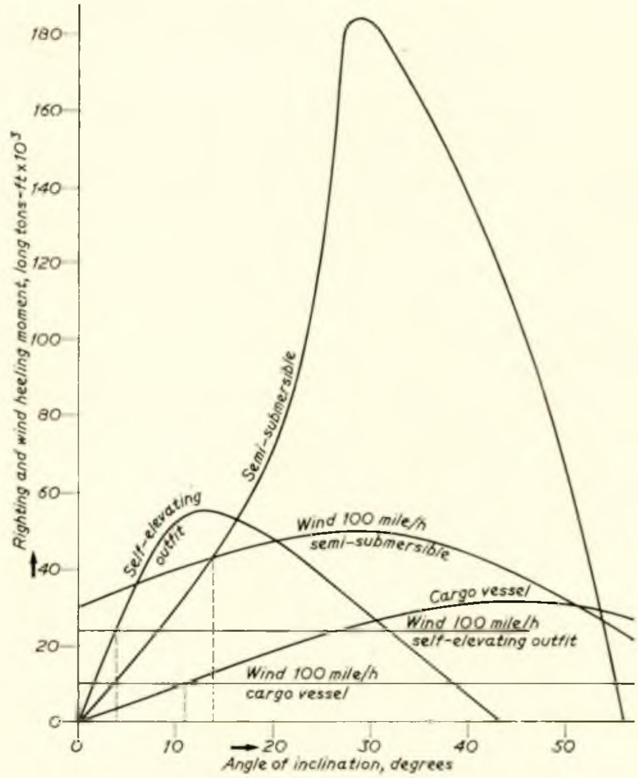

FIG. 15—*Stability curves*

of drilling operations even in 15-ft seas in some parts of the world.

Thus far almost all studies on platform movement have been made for regular waves. A random pattern still has to be studied, but will take engineers considerable time. Another attempt to show expectable movement is shown in Fig. 14, derived from model tests of a semi-submersible. It is deduced from these tests that the outfit can continue to drill in extremely rough seas; however, it must be stated that the motions of the platform would make physical handling of the drill pipe by the crew, unsafe and impracticable long before over-stressing of the drill-string were to occur.

The author presents these two illustrations as first attempts, and very much hopes that others may in the future be able to present and discuss a more detailed investigation.

STATIC STABILITY

Essentially, the vessel-shaped drilling outfit may be treated as a ship and the normal and damage stabilities investigated accordingly with well-known rules and procedures. The semi-submersible is a very different type of body; it too, however, is a floating structure exposed to all the forces of wind, wave and current, and the chances of damage or of loss of integrity. It must be designed and constructed in such a fashion that it remains safe and of no danger to the personnel on board or to other users of the oceans. In respect of the last consideration, it will, of course, be appreciated that a semi-submersible is a non-powered structure, is towed by other vessels and is anchored at a site when performing its intended function.

Fig. 15 illustrates the static stability of a self-elevating outfit and a semi-submersible and for purposes of comparison the curve for a 10 000-dwt cargo vessel is included. The curve for the self-elevating outfit is based on the condition when the outfit is on a move from one location to another in the same oil field; the legs would be fully retracted, or almost so, and extend up from the carrying hull. The outfit is then a heavily-loaded barge or pontoon. For the semi-submersible, the condition is for the outfit submerged to drilling draught (some 50 ft). The very large GZ values for these drilling platforms should be noted.

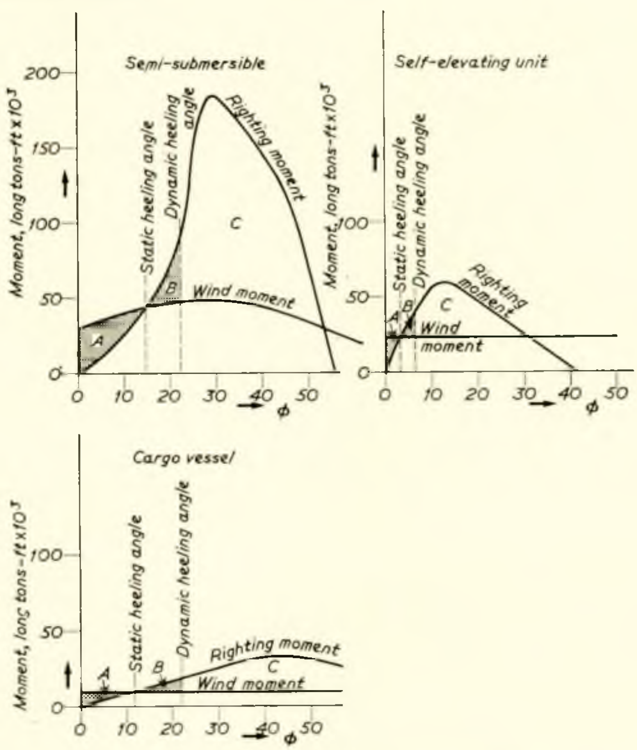

FIG. 16—*Static and dynamic heel angles*

Fig. 16 extends the illustration to show static and dynamic heeling angles. As is well known, the righting energy of the body equals the heeling energy executed by the wind when areas A and B are equal. Area C represents reserve energy. The rather slow build-up of righting energy for the semi-submersible should be noted, also the very large reserve righting energy. These outfits present rather large areas to the wind and do not have very large water-plane areas; their righting arm, however, is quite large and this gives them the considerable righting moment.

Finally, some comment on damage stability. This subject requires very careful consideration, for flooding of a corner column of a semi-submersible can lead to a very large angle of heel before correction by re-arrangement of ballast. It is desirable, therefore, that ballasting of the outfit be in the corner columns, but this is not practicable with several designs and the bottom-grid usually carries the ballast. It is then imperative that the vulnerable corner columns be compartmented both transversely and vertically. Some designs have incorporated a foamed plastic of very high porosity, but negligible permeability, as a filler in these columns.

Mention has been made previously of the sensitivity of a semi-submersible in respect of carrying capacity for the non-marine items. Fig. 17 illustrates the transverse stability for deck loads of 1000, 1500 and 2000 tons. The rather rapid decrease in GM should be noted.

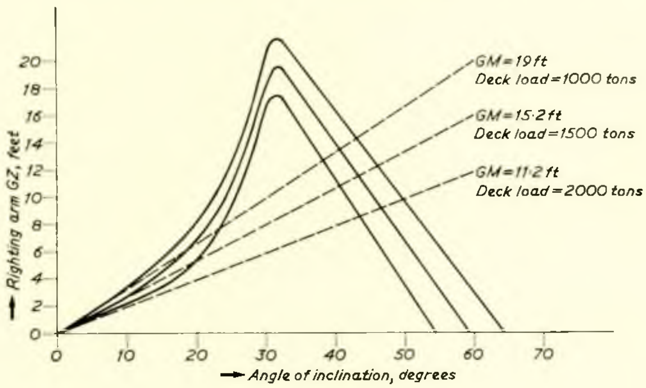

FIG. 17—*Transverse stability of semi-submersible for various deck loads*

ANCHORING

The purpose of anchoring is to maintain the drilling outfit on location under all circumstances of weather, or to arrange for the necessary freedom to survive the maximum anticipated conditions and to take up station once those conditions have abated. An anchoring system has but a very limited effect on the oscillatory motions of the floating body. Wire rope, chains and combinations of the two have been employed by designers and protagonists of all three systems argue with conviction based on practical experience, extensive mathematical investigation, operational considerations and sometimes, the author believes, on hunches founded on prejudice. A high seas drilling outfit is a mobile factory, its sole output which has any value being thousands of feet of hole drilled into the earth; this may only be accomplished when the outfit is on location and this must frequently be changed. When under tow, or moving self-propelled, when mooring-up and when disengaging, nothing to achieve an earning-power is being accomplished. Even worse, there is no return from all the operations of drilling involving round-trips of the drill pipe, changing of the drilling-bit, mud-conditioning, hole protection, by insertion of casing, and others. Only when the bit is actually on bottom and making a hole and when well-bore investigations are in progress is anything accomplished. Appendix B lists, from actual operating experience, the time-expenditures on various operations and on delays occasioned by mechanical troubles or by the marine environment. Only about one-third of total time is spent profitably, a further one-fifth is occasioned by essential operations and yet another one-fifth on engineering difficulties associated with the drilling. Over a quarter of the time is spent on marine operations or lost through weather.

The ideal mooring system should have sufficient rigidity to prevent the outfit from being moved off the hole. A small movement of the body should then cause a large restoring force in the mooring system, but this system should also be sufficiently flexible that motions due to waves do not cause undue high loads in the anchor lines. An ideal mooring system should provide a rapidly-increasing restoring force, to the limit of the allowable anchor-line loads. Thereafter, further movement of the vessel should not cause any further increase in restoring force. All mooring systems developed so far are much less than ideal. They are initially very flexible, allowing considerable vessel movements without building up sufficient restoring forces; only with greater movement does the progressive build-up attain sufficient and rapidly increasing magnitude. The spring characteristics of these systems may be improved by spring-buoys, constant-tension devices or other innovations, but these have all tended to be too cumbersome and obstructive to quick mooring and disengagement, and have sometimes been a hazard to operating personnel. Mooring systems are still a compromise and, within the bounds of compromise, it is well worth while studying sea conditions in each area in as great a detail as possible and attempting the configuration best suited. It is impracticable to change from wire to chain and to change anchor winches, but the geometry of the mooring lines (length and relative angles) does repay careful study.

The physical advantages of wire rope are ease of handling and ease of determining line tension. The disadvantages are the very massive anchor line winches required and the fact that, with all lines spooled, a considerable increase in outfit dead-load is imposed at the most disadvantageous situation,

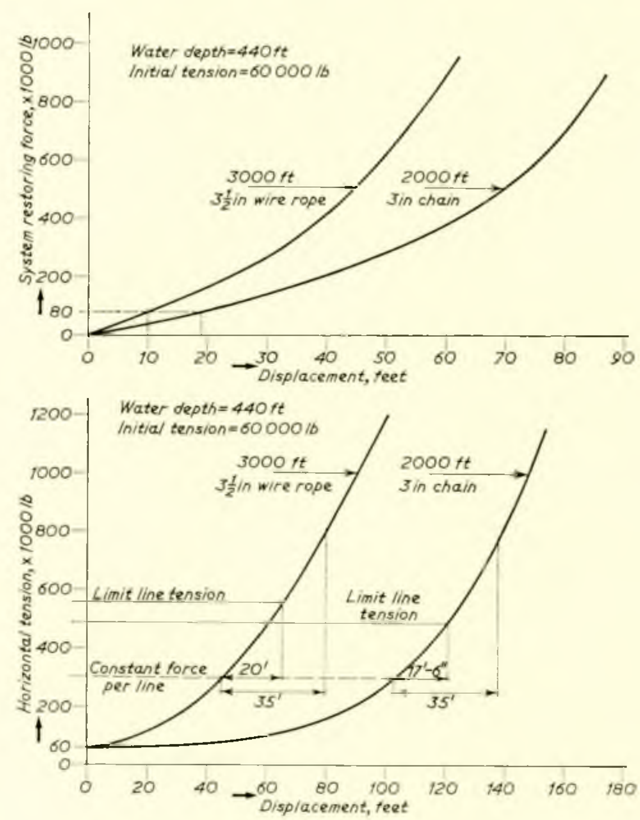

FIG. 18—*Predicted performance of wire rope and chain anchor lines*

high on the working deck. Chain may be stored in a locker and this could conceivably be arranged low down in the structure. In addition, the retrieval winch would be far less heavy and bulky than that for wire lines. The weight per foot run for chain is, however, four times that for wire. For a deep-water semi-submersible, intended for services in the roughest areas of the world, the all-up weights of lines and winches, employing an eight-point system, would be 800 tons for wire rope and 1150 tons for chain.

From mathematical analyses, the author's colleagues have shown that wire rope is to be preferred over chain on the score of restraint of the drilling outfit and lesser surge. Fig. 18 shows the theoretical performance of 3½-in wire-rope and 3 in chain, with effective lengths of, respectively, 3000 ft and 2000 ft, and a water-depth of 440 ft. The upper part of the figure shows expected performance for initial tensions of 60 000 lb. During normal weather, taken as 40 mile/h wind and one knot current, the calculated necessary restoring force would be 80 000 lb; the resultant displacement of the outfit would be 10 ft for wire-rope and 18 ft for chain. For the requirements of the drilling operation, then, wire-rope should be much superior to chain. The lower part of Fig. 18 shows the calculated relationship between line tension and displacement. For peak storm conditions of 140 mile/h wind and 2½-knot current, both broadside to the outfit, the line tensions would be of the order of 300 000 lb. If it be assumed that the maximum loading on either wire or chain should not be more than 50 per cent of their breaking strengths, then the allowable surge of the outfit will be some 20 ft for wire and 17·5 ft for chain. It is to be noted that the dimensions of the outfit taken for this example are such that the surge will be of the same order of magnitude as the height of the wave—if a 70-ft wave were to be expected then the amplitude of surge would be 35 ft. The resultant tensions in both wire and chain would be close to 80 per cent of ultimate breaking strength. At this point the author realizes that he has chosen an example that leads to discouragement and dismay. He has quite overdone his "maximum" approach. It must be accepted that these curves relate to an outfit not yet designed nor constructed, but under consideration. It must be further accepted that in an area of such enormous peak storm conditions the outfit would be orientated to take the weather head on, when the resultant forces would be very substantially reduced. Consideration is also being given to an arrangement of a single storm anchor, from which the outfit would ride after detaching from the well-head.

Now obviously it is insufficient to consider the mooring lines solely; the anchors themselves are an integral part of the system. Assurance is given that the system as a whole has been well studied, but there is insufficient space in this paper to go into more detail. The most popular anchor is the Danforth-Jackson, and the largest manufactured so far, of 30 000 lb, are employed on the semi-submersibles operating in the North Sea.

DYNAMIC STATIONING

The first oil-industry application of dynamic stationing was to a small vessel employed in shallow-hole geological core-drilling. The project was in several thousand feet of water where a static mooring system was clearly impracticable.

The complexity of static anchoring systems, their prime cost and weight and operational difficulties lead naturally to consideration of this form of stationing for deep drilling. The employment of a series of "thruster" units has been investigated in some detail, both within the author's department and by a Government project. Reference is made to several published works[12, 13, 14, 15], in which the system of position determination, calculation of necessary restoring forces and commands to the thruster units are well described. The power involved becomes very considerable and extremely expensive, the more particularly if sufficient is provided to meet peak demands. Such demands would be of relatively short duration and in aggregate a very small, almost negligible, percentage of the total time during which the outfit is on the high seas. In place of traditional Diesel-engined power plants, consideration has been given to peak-power, gas-turbine units or even steam turbo-electric power (though a conventional marine steam power plant on a space-frame semi-submersible is a formidable concept). There is a cross-over point where dynamic stationing is economically justified over static mooring systems. Disconcertingly, present calculations show this to be between 2000 ft and 3000 ft of water. Reverting to hunch-estimating, the author, who is greatly exercised by the operational problems of static mooring, believes that dynamically-stationed outfits eventually will be justified for 1500 ft of water and maybe somewhat less.

DESIGN OF A SEMI-SUBMERSIBLE OUTFIT

The semi-submersible is an attempt and a very successful one, to achieve a stable floating platform. To achieve this, attention has been focussed on water-plane area, a wide beam, a large total amount of inertia (masses far out), a high freeboard, and a deep draught. Additionally, vertical surfaces in the sea and above should be as limited as may be practicable, to minimize forces resulting from waves and wind. As always, some of these desires are conflicting, particularly when married forcibly to the requirements of drilling machinery placement. The semi-submersible (see Fig. 5) has a large bottom structure to provide buoyancy, large corner columns to achieve acceptable water-plane area and a large beam. A deep draught can only be obtained by ballasting and a high freeboard is essential for a wide range of stability. Problems of construction may not be taken too greatly into account when a design is conceived, but towability and transit through anticipated narrow passages certainly must be; the beam dimensions of at least two units have been restricted to permit transit of the Suez canal.

With the open tubular frame and bracings of a typical outfit, it is well-nigh impossible to find compartments for machinery, other than that connected with bilge pumping and transfer of water, fuel and possibly reserve drilling mud, which fluids are carried in the bottom members. So, because only the top is left (and perhaps because drilling is traditionally an open-air venture) all machinery, accommodation, storage and the power plant are generally placed on one top deck, but sometimes on two. This leads to rather a high centre of gravity, and an acceptable metacentric height can only be attained by juggling with the water-plane area, beam, draught and freeboard.

The first essential step is a listing of all fixed items of equipment and weight, plus all variable loads such as pipe and consumables, together with a preliminary sketch of the layout. Where to place the actual drilling floor (derrick and hoisting gear, drill-pipe rotating machinery) must be decided. For the least movement, the centre of the outfit is the logical place, but this would limit its use to sea-bed well-control gear, otherwise there would be problems in moving away from a completed well, or in moving off in exceptionally bad weather. Also, the arrangement of the drilling machinery is more convenient if the drilling derrick is toward an end of the outfit. Next to be decided is whether the outfit shall be for floating duty only, or shall be arranged to serve also as a sit-on-bottom unit. It must finally be decided whether the best possible dynamic behaviour will be sought, at the expense of unhandy, slow and expensive towing, or whether an attempt should be made to cater for a reasonable towing performance when at minimum draught. Weather design criteria are then set, either for the specific area of operation, or for world-wide use (the latter would reflect on load-carrying capacity).

A judgement can then be effected on freeboard and on drilling draught. Anticipated buoyancy and ballast quantities are then resolved and preliminary sizing for the tubular frame is accomplished. After this it is usual to investigate the dynamic behaviour by model tests. More detailed design follows and a return to the test tank may still be necessary.

As for the self-elevating outfit, little exists in the form of authoritative rules and regulations. The structure must be designed in accord with standard engineering practices, with attention paid to those aspects where marine practice can be of aid and is applicable, or may prudently be followed. There is close contact with the classification societies, American Bureau of Shipping and Lloyd's Register, and these are developing their rules at the present time. Meanwhile, it is the practice to review the designer's calculations to determine if the assumptions and stresses are reasonable when compared with similar successful designs. The author would like to quote from an A.B.S. publication[16].

"The history of marine construction, both fixed and floating, is primarily a record of trial and error. Early ships were patterned after still earlier ships and generally differed only slightly in arrangement and size. If a casualty occurred scantlings were made heavier. On the other hand many years of successful operation were required before even slight reductions were considered. It has been the practice, generally, to build a ship to a certain standard of strength, not because it was subjected to a calculated loading which dictated the strength, but because a majority of similar ships had been successful in service. The development of drill rigs has followed a similar, but less conservative philosophy. Offshore drilling structures were designed in spite of the lack of historical data by which designers could be guided.

The American Bureau of Shipping has no published rules for structures of this type but over the years has developed certain standards which are used to evaluate the structural efficiency of new proposals Whether or not these standards are ultra-conservative is difficult to determine. It is an established fact, however, that for the most part, structures predicated on these standards have withstood extreme storm conditions, including hurricanes, during operations in the work for which they were designed. Of major concern to the American Bureau of Shipping from the point of view of classification, or from the standpoint of assignment of load lines, is structural strength and seaworthiness. Barge type hulls, submersible columns and the operating platform structure are all reviewed and analysed. The suitability of piping and associated machinery and pumps, together with the source of power used for ballasting is also a concern. Machinery, piping etc., which are used solely in the drilling operations at the site, are not considered as being within the realm of classification".

And also:

"The drilling structure has been changing rapidly in design as the designers have gained experience. As mentioned earlier while it takes many years of successful operations before reductions in scantlings for ships are permitted, this is not the case with drilling structures. It is noted that if a certain drilling structure is to be duplicated, the designers do not hesitate to take advantage of reductions which experience has shown to be allowable. It is not possible as yet, however, to develop specific requirements which would reflect minimum standards for drilling structures".

In the author's experience, competent investigation into the structural soundness of a semi-submersible design demands a very high level of technical knowledge and involves extensive use of computers for stress determinations from formulæ which become extremely involved. Investigations should be made for the conditions of towing, and submergence at maximum draught and at drilling draught. From these investigations an operating handbook must be prepared, with clear instructions as to procedures to be followed during the various operations and with the approach of, and during, storm weather.

MATERIAL SPECIFICATIONS

The author decided not to enter upon detailed discussion of material specifications, regarding neither quality nor physical dimensions. With the appreciation that some information on these aspects is still essential, Appendices C and D have been added, with details of the main structural members and material specifications for the self-elevating and semi-submersible outfits respectively.

CONSTRUCTION PROCEDURES

It is convenient to discuss the construction of self-elevating outfits and semi-submersibles separately, and to dismiss vessel-type outfits with little comment. Although a vessel built, or modified, for drilling duty may have certain special features and may even be a siamese (catamaran), the overall construction follows well-established principles, and no great deviations from normal shipyard and shipbuilding practices are involved.

Self-elevating Outfits

These outfits are, primarily, steel structures provided with means of floatation to permit moving between locations and countries. It has been convenient for them to be built in and by a shipyard, but this practice is by no means essential, or even universal. One of the earliest and very well-known series of outfits of this type has always been built on land adjoining a river or on a beach. The legs offer obvious possibilities for sub-contract work and for section-by-section assembly; installation may be either at the prime building site or at another, sometimes distant, final assembly point.

With the "beach-built" outfit, the main hull or pontoon is completed, with all major between-decks equipment and machinery installed, also the jacking mechanisms and power. Short sections of legs are then installed through the hull and this raised some distance above the land. The whole outfit is then "walked" into the river by rocking over masses of temporary mounds of earth; the rocking is accomplished by alternate raising and lowering of the legs at the end of the hull. Once afloat, the legs are lowered to, and penetrate, the river bottom, and leg sections are added in turn, with the hull being made to climb the legs so as to provide a rising working platform for the construction and welding crews. Since the legs on modern outfits may be several hundred feet in length, the hull has to be raised to a very considerable height; therefore, these outfits are moved down river to deeper water so that the height of the hull above water surface may be kept within psychologically acceptable limits.

All other self-elevating outfits are assembled with the hull built on a slipway and the legs lowered into the jacking mechanisms when the hull is floating. Figs. 10 and 11 illustrate stages in the construction of a hull and of assembly of the legs. The legs, even in relatively short sections, are very heavy, the order being two tons per foot of length and either large shipyard cranes, or port authority cranes are usually employed for this. However it can occur that insufficient height is available for placement of these sections, or a cross-river obstruction has to be passed (electrical overhead lines, bridges etc.) down stream of which no heavy lift equipment is available. A very excellent example of this was reported recently[17]. A U.K.-built drilling outfit has legs of 278 ft total length. The initial assembly of 134-ft sections was performed at the yard and the outfit was then towed down stream to deep water, where sections of 36 ft at a time were added. These sections were handled on the hull by temporary king posts, with lifting power provided by the drilling platform anchor winches. The deep-water location had 150 ft maximum water depth and some 80 ft of very soft bottom; the legs penetrated this bottom fully and thus the outfit on completion was probably only just out of the water, or not at all.

Semi-submersible Outfits

By their very size, these outfits present extreme problems of construction and several novel solutions have been employed. A well-known triangular design has been built in the U.S.A., Japan, the U.K. and Holland, and three procedures have been used. For the U.K.-built outfit, a slip was used and launching performed with an auxiliary buoyancy and support unit (a pontoon at the open after side). The author has been unable to locate any published literature or paper on this construction and launching, but various journals carried photographs at the time. For the Dutch-built unit, the sequence of erection is shown in Fig. 19. The three base pontoons were constructed and floated into correct position and then the main corner columns and bracing, all prefabricated in sections, were added. To maintain truth in the structure, additional temporary pontoons were used between the corner units to support the lower horizontal tubular members.

The procedure in the Japanese yard was superficially

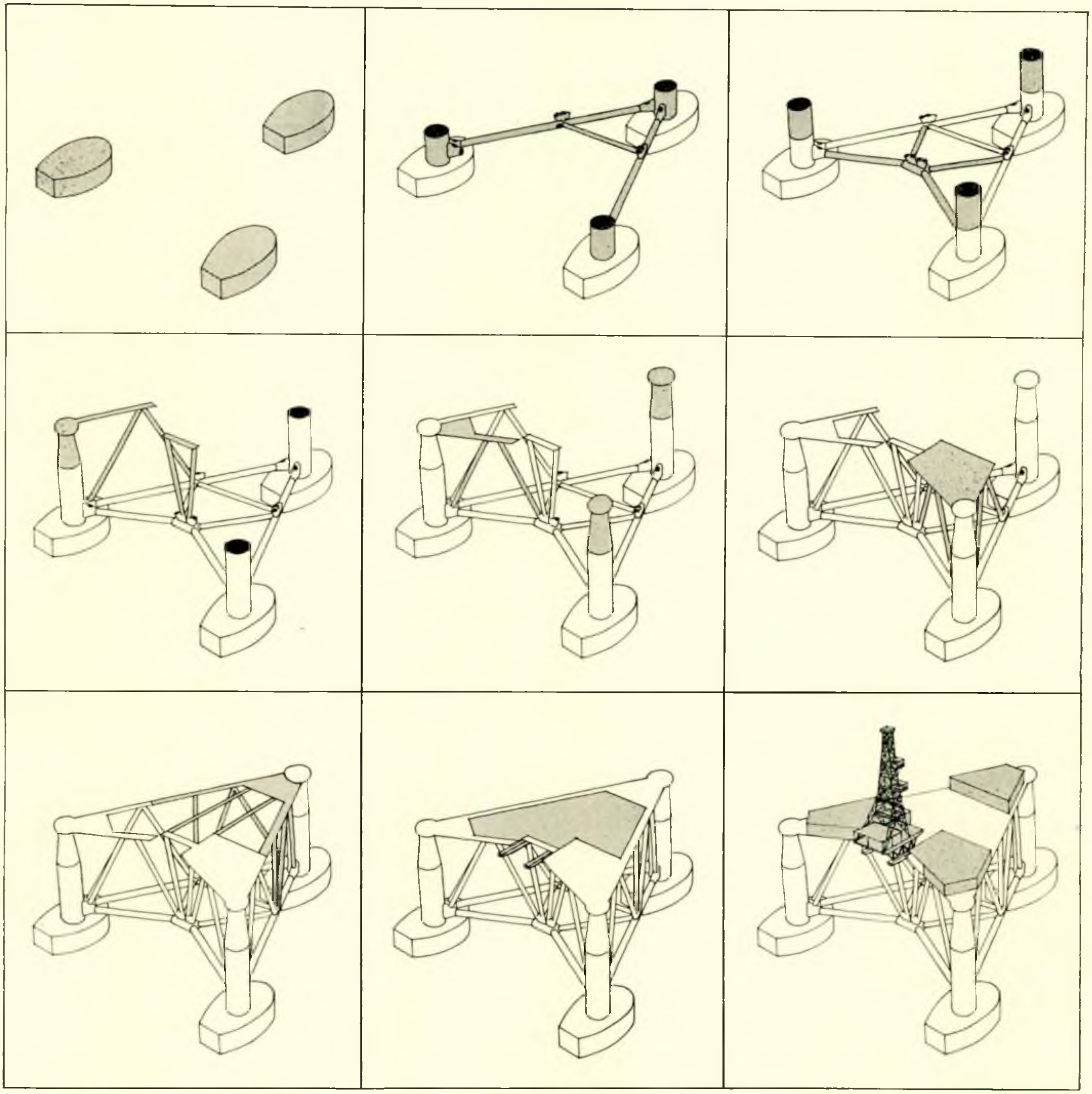

FIG. 19—*Building sequence of Sedco drilling outfit*

similar, though basically different. There, the corner pontoons were sunk in some 25 ft of water on to specially-prepared piled foundations. The horizontal tubular members were brought in by barge and crane and offered up to the stub corner columns. Additional piled foundations were provided to support the lower members during and after attachment and the rest of the structure was completed with prefabricated sections placed by cranes. All fitting-out and machinery installation was done at this same site and only then were the corner pontoons de-ballasted and the outfit taken for sea trials. On tow, this outfit floats with one to two feet freeboard on the corner pontoons, so this procedure was practicable.

The Staflo semi-submersible building at a U.K. yard was on a slip. The beam of this outfit exceeds that of any vessel and the structure has had to be "squeezed" to allow assembly between the yard cranes. The main supports for the outfit are the four large torpedoes of 230-ft overall length. Three of these tubes have been placed at the correct spacing, but the fourth (outer port) is placed close up to its neighbour. The structure was completed on the slip and launched and the bracing members on the port side then cut, the tube moved out to correct position and connecting members extended accordingly (see Figs. 20 and 21). Fitting out of this unit should be well-advanced at the time of presentation of this paper.

During construction, overall supervision is provided by an

FIG. 20—*Construction of Staflo semi-submersible*

owner's representative, with continuous and full examination and inspection of material specification and quality by recognized authorities. The American Bureau of Shipping or Lloyd's Register of Shipping perform these inspection services and specialized welding inspection teams are also brought in. The designer of the outfit, or other consultant, is also asked to provide resident engineering advice and control. When the structure nears completion, it is usual for the owner to provide a team of drilling experts to assist in the placement of drilling machinery and the installation of the very specialized electrical circuit and fluid handling piping. In the author's experience, shipyards schooled in the precise designing, draughting and machinery placement of ships have been taken aback by the somewhat freer approach of the drilling fraternity. The latter are accustomed to placing their machinery on land, with a surface of invariably regular bearing value. The machinery is not spotted to engineering precision and piping and other interconnecting media are made to fit, or have certain flexibilities to allow for misalignment. The concept of planning everything to the uttermost detail is foreign to this experience and the mental approach developed by it. The author believes there to be merit in applying some part of this thinking to rig construction in yards; he has seen undue valuable staff and drawing-office time wasted on worry over the placement of the most simple item of equipment. Granted that all major equipment items and heavy ones must be located properly, their loading assessed, and transmittal to the main structure evaluated and provided for, but there are numerous small items that can be placed, or installed, in sites properly designated, and then joined up by "plumbers", a specialized team, expert in working from the most simple single-line layout diagrams.

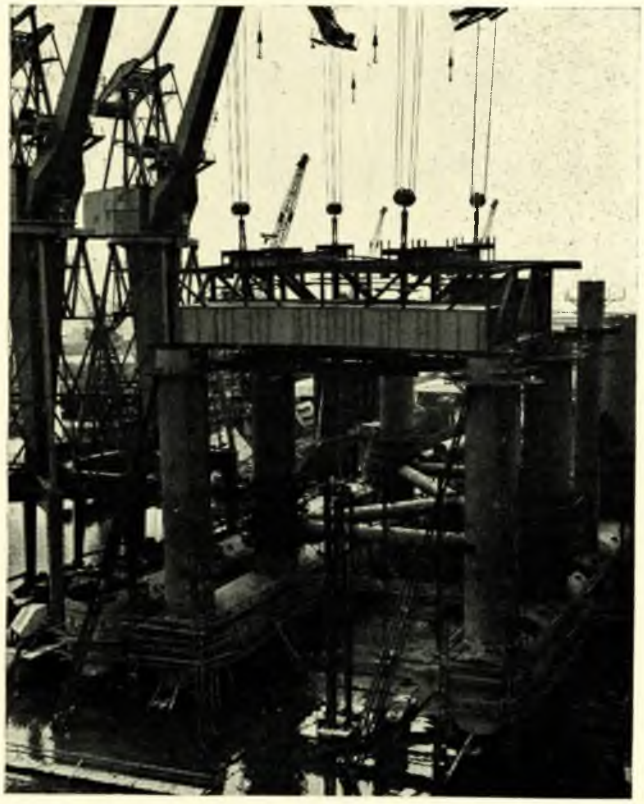

FIG. 21—*Further stage in construction of Staflo*

A problem not yet resolved is weight control. In the author's experience, many designs of semi-submersible outfit have increased very significantly in total weight at each stage from conception through model testing, broad design, contract placement, detailed design and shipyard construction. It is significant that none of the increase has been due to change in thought from the drilling department and the imposition of greater loads from machinery, equipment or supplies. The increases have come entirely from those aspects on which there is little experience; anchoring equipment, bilge control pumps, hull design, i.e. the internal strengthening of the main tubulars, and tubular joint construction. Short cuts in estimation of weights, ignorance, i.e. lack of empirical knowledge, of sectional unit weights have been major causes leading to severe and shocking awakenings of considerable weight increases. The situation stems from the fact that owners, designers and builders are all dealing with a new conception, a new form, a device for a new duty, and experience still has to be gained so that "rules of procedure" may be elaborated. Above all, few of those associated with construction of these outfits and even few on the design side, have appreciated just how sensitive a semi-submersible is to the disposition of mass and weight and what very large effects may be made on the static stability or load-carrying capacity by changes from the original conception and weight estimations. The author's company has sought to follow the principles enunciated by the United States Navy and described in a recent paper[18]. All design engineers, consultants and constructors associated with the production of an outfit either for company ownership or contract operation are required to study this paper.

The author would finally make a plea for attention to the "finish" of the fitting-out, not because it is poor, but rather because it is too good. A drilling-outfit is a place of work and exposed to the elements; only the living-quarters require a higher standard of finish and this should not be overdone. The quarters should not be unduly spartan, but should be simple and employ materials that may easily be cleaned and retain a sparkling surface. The author rejoices in traditional wood fillets in his car, but not on a drilling outfit.

ACKNOWLEDGEMENT

The author desires to acknowledge that he has prepared this paper with the assistance of staff of his department, each experienced in various specialist spheres of design or operational activity. The opinions expressed are his own and also the method of their presentation; the studies on the design and construction of offshore drilling outfits performed by these specialists, under the author's executive control, have made this presentation possible.

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APPENDIX A

STAFLO DRILLING OUTFIT—EQUIPMENT AND WEIGHT LIST

Weight (long tons)

011 *Equipment in Torpedoes*

The four pump rooms (one in each torpedo) contain the pumps for cooling water, drill water, potable water, fuel and fire fighting and for the hydraulic power units for the remote control ballast system.

The six ballast pumps have a capacity of 2100 U.S. gal/min each and are driven by 64 hp motors.

Total 115 tons.

012 *Machinery Spaces (Engine Room etc.)*

5 English Electric 12-CSV 1450 hp Diesel engines.
3 Smit constant-current d.c. generators, 1000 kW.
2 1000 kW English Electric a.c. generators.
3 600 gal/min Meco distilling units.
3 Gardner Denver type WEG, air compressors delivery 286 ft^3/min, discharge pressure 175 lb/in^2 gauge (100 hp each).
3 air receivers 1128 gal capacity.
2 Babcock and Wilcox exhaust heat boilers steam capacity 1660 lb steam/h at 75 lb/in^2 at full load of Diesel engines.
A.C. and d.c. switchboards.

Total 230 tons

Weight (long tons)

013 *Equipment on Main Deck*

4 Clarke Chapman anchor winches each with two barrels arranged in tandem, capacity 3500 feet, 3-inches diameter steel wire. Duty in low gear: 122 long tons at 20 ft/min. In high gear: 19·6 long tons at 125 ft/min. Motor 250 hp at 600 rev/min.
2 Clarke Chapman cranes, hoisting 31·25 tons at 20 ft/min (radius 60 feet) to 5 tons at 120 ft/min (radius 60 ft) or 15 tons at 100 ft radius. Hoisting motor 65 hp.
8 30 000 lb Danforth-Jackson anchors.
2 Pickering electric lifts to central pump rooms
1 Life boat, rafts, etc.

Total 870 tons

014 *Drilling Equipment*

1) Draw works:
National 1625-DE, electric-driven, complete with sand reel, 1½ inch drum grooving, dynamatic brake.

2) Mud pumps:
2 National N-1600 with K-20-5000 pulsation dampeners.
1 National N-900 with K-20-5000 pulsation dampeners.

3) Derrick and substructure:
140 ft × 30 ft base, 1 100 000 lb capacity, Lee C. Moore welded-type, single-well, dynamic derrick 30 ft × 30 ft × 40-ft high substructure with 400-ton rotary load and 20 000 ft 5-in drill pipe set back capacity.

4) String-up equipment:
   a) National 760-F crown block for 1½ in wire line (7 sheaves).
   b) National 660-H-500 travelling block (6 sheaves).
   c) National Type 1324 swivel.
   d) B.J.-5500 Dynaplex hook.

5) Rotary table:
National C-365 36½ in draw works driven rotary.

6) Mud-mixing and de-sander pumps:
4 Mission 6 × 8 centrifugal pumps, all powered by 440 V., a.c. electric motors.

7) 9 Smit constant current d.c. motors, assigned as follows:
2 1200 hp—draw works
2 800 hp—Mud pump No. 1
2 800 hp—Mud pump No. 2
1 800 hp—Mud pump No. 3
2 500 hp—Cementing unit
Controls and blowers.

8) Dry mud and cement storage equipment:
12 Halliburton P-tanks with 1360 ft³ capacity each.

9) Auxiliary equipment:
   i) Mud-conditioning equipment
   ii) Instruments and well control gear
   iii) Mud storage hoppers
   iv) Marine conductor tensioning devices
   v) Air hoists for material handling
   vi) Well-cementing unit
   vii) Well-logging unit

Total 597 tons

Weight Summary (long tons)

a) *Lightweight*			
1) Equipment			
011 in torpedoes	115		
012 in engine room	230		
013 on main decks	870		
014 drilling equipment	597		
2) Accommodations etc.	311		
3) Steel structure	5575		
Total a)		7698 tons	
b) *Variable Load*			
1) Maximum individual storage capacities on deck			
Bulk mud	200		Recommended maximum operational variable deck load for North Sea: total 1500 tons
Bulk cement	300		
Chemicals	20		
Liquid mud	460		
Drill pipe and casing	700		
Conductor and well-head equipment	300		
	1980		
2) Fuel	464		
Drill water	300		
Potable water	118		
	882		
Total b)		2382 tons	
c) *Ballast Water* for 50-ft draught		2000 tons	
Total displacement		12 080 tons	

Appendix B

TIME-EXPENDITURE, FLOATING DRILLING OUTFIT

A semi-submersible, drilling eight to ten 8000-ft wells per year, expends time in the following proportions, expressed as percentages.

	Per cent	Per cent
Drilling Operations		
On bottom	21	
Round trips, routine operations	13	
Casing and cementing operations	8	
Sub-total		42
Engineering Studies		
Operations for geological evaluation	9	
Sub-total		9
Mechanical Operations or Delays		
Difficulties with well-bore or drill pipe	10	
Equipment maintenance	5	
Equipment handling (well-control items)	7	
Sub-total		22
Marine Operations		
Anchoring, disengaging, and tow	9	
Sub-total		9
Marine Delays		
Downtime due to weather, on location	7	
Downtime due to weather, moving	11	
Sub-total		18
Check-total		100

APPENDIX C

STRUCTURAL STEEL IN A TYPICAL SELF-ELEVATING UNIT

Hull

Most of the main deck plating between the legs is $\frac{7}{16}$-in thick, with two 18-ft wide strips $\frac{3}{4}$-in thick along the longitudinal edges. Plates forward of the legs are typically $\frac{3}{8}$-in thick, with $\frac{5}{8}$-in thick plates along the longitudinal edges. Aft they are $\frac{5}{8}$-in thick. The area around the spud well is $1\frac{1}{4}$-in thick.

The bottom shell plating is mainly $\frac{7}{16}$-in thick, again with two 18-ft wide strips along the longitudinal edges of $\frac{3}{4}$-in steel. The area around the spud well is again $1\frac{1}{4}$-in thick.

The side shells are $\frac{7}{16}$-in thick, the longitudinal bulkheads are somewhat heavier and vary between $\frac{1}{2}$-in and $\frac{3}{4}$-in. Stern and bow-plating are $\frac{7}{16}$-in and $\frac{1}{2}$-in thick; transverse bulkheads vary between $\frac{1}{2}$-in and $\frac{7}{8}$-in, depending on location.

Rolled sections up to and including $\frac{7}{16}$-in thick are A.B.S.-grade mild steel; plates under $\frac{1}{2}$-in are A.B.S. grade A, from $\frac{1}{2}$-in to 1-in are A.B.S. grade D and over 1-in A.B.S. grade E.

Legs

Of 10-ft or 12 ft-diameter with wall-thickness 1-in to $2\frac{1}{2}$-in. Internal ring stiffeners 12-in × $\frac{1}{2}$-in with 12-in × 1-in flanges. Steel is semi-killed, niobium-treated, normalized, according to B.S. 1501/213. Impact value 35 ft lb at −15°C.

Jacking frames

Very heavy sections up to 6-in thick.

APPENDIX D

STRUCTURAL STEEL FOR SEMI-SUBMERSIBLE DRILLING OUTFIT

Main dimensions:

Length (excluding anchor racks) ... ... 233 ft
Width (excluding anchor racks) ... ... 200 ft
Height from keel to lower deck ... ... 93 ft 6 in
Height from lower deck to top deck ... 19 ft 8 in and 14 ft 9 in

Torpedoes:

Length ... ... 233 ft
Diameter ... ... 19 ft 8 in
Steel plating ... ... $\frac{13}{16}$ in

The torpedoes are stiffened by scantlings, consisting of an 18-in × $\frac{11}{16}$-in web and a 6-in × 1-in flange. Distance between scantlings 4 ft. The torpedoes are subdivided in compartments by watertight bulkheads. Thickness of bulkheads $\frac{3}{4}$ in.

Columns:

The diameters of the columns are 23 ft, 13 ft 2 in, and 8 ft 2 in. The plate thickness of the column varies from $\frac{5}{8}$ in to 1 in. In the four corner columns there are watertight bulkheads with a thickness of $\frac{3}{4}$ in.

Bracings in the lower hull:

The diameters are 5 ft 6 in and 3 ft $3\frac{3}{8}$ in. The wall thickness is $1\frac{3}{8}$ in.

Deck:

The deck plating is $\frac{1}{4}$-in thick, but locally heavier ($\frac{3}{8}$ in). The deck trusses consist of rolled sections or built-up girders of various sizes. The heaviest girders are 40-in deep and 12-in wide, with maximum plate thickness of $1\frac{1}{2}$ in.

TABLE II.—STEEL SPECIFICATION

Plate thickness	Lloyd's Register grade	Ultimate tensile stength tons/in^2	Charpy V-notch	Carbon content
$t \leqq \frac{3}{8}$ in	A	26 to 32	Not specified	Not specified
$\frac{3}{8}$ in $< t < \frac{3}{4}$ in	D	26 to 32	35 ft lb/min at 0°C	0·21 per cent maximum
$t \geqq \frac{3}{4}$ in	E	26 to 32	45 ft lb/min at −10°C	0·18 per cent maximum

Discussion

Mr. G. C. Eddie, B.Sc. (Member) said that he had greatly enjoyed the account of these offshore drillings, and the film. They were very bold ventures into the unknown in the tradition of the great early years of British engineering and shipbuilding.

It seemed from the film that both his and the author's industries used their equipment as icebreakers. One difference was that what Shell would regard as excessive movement of the working platform would be regarded as imperceptible by his own Authority. As the film showed, they were both engaged in transferring their products in the open sea from ship to ship, lashed together with some sort of fenders in between. In fact, both organizations were concerned with a variety of equipment for use in the open sea. That included various kinds of ship and, also, things very different from the orthodox seagoing vessel. It was good to know, incidentally, that this Institute felt that the definition of marine engineering covered all such things. In fact, marine engineering was rightly becoming defined as the design and construction of any piece of equipment that had to work in or on that very hostile environment, the sea. Most marine engineers had been concerned with the propulsion of ships and it might be fair to say that, even in the recent past, the designer was justified in thinking that the most hostile thing in the environment was the marine engineer himself. However, in the design of offshore rigs there were obviously other hostile elements—for instance, waves and swell.

Static platforms gave a very good opportunity to measure wave profiles and wind velocities accurately; he wondered if there had been any attempts to do so and simultaneously to measure the movements of the rig, so as to correlate model and full scale, thus to test theory and examine whether model representations of sea states were sufficiently accurate to give useful results.

In the last year or two there had been efforts with the guidance of B.S.R.A., to provide a basis for the design and development of ships and machinery by making measurements on the full scale in service conditions. Among those active in this had been Shell Tankers and his own Authority, both user organizations, one belonging to an industry already with a broad basis in modern science and technology and the other deliberately importing research and development staff from the aerospace industries. He was a little surprised, therefore, to find that the rigs described in the paper had been designed entirely by the classical methods of the shipbuilder—prediction based on model tests and calculations. Was any attempt being made to carry out measurements on the full scale in service conditions, to guide future design?

This approach could be valuable when, for instance, considering fatigue of the structures which, he understood from the lay press, did occur. In these circumstances it would be useful to know the real stresses developed in various service conditions. Perhaps Mr. West would say whether, for instance, the figures given for loads on mooring ropes were calculated or measured.

The possibility of resonant conditions occurred in various mooring problems. For instance, there had been a paper given to the Institution of Civil Engineers by Roberts of the Hydromechanics Research Association on the resonance of tankers moored to quays equipped with fenders. It would be of interest to know if any calculations had been done on the natural frequencies of moored drilling rigs, and whether this was a significant problem for such equipment.

There was one point of detail on mooring systems that he wished to raise. Mr. West referred to the undesirability of having big winches mounted high above the centre of gravity. The solution propounded was to use a windlass and chain and put the chain locker low down. Mr. West might know that a design study had been carried out for a trawl winch which took the form of a certain type of mine-winding drum with the warp being coiled and stowed in cable tanks down in the hull.

In his Thomas Lowe Gray lecture to the Institution of Mechanical Engineers, Mr. Avery had indicated that there were severe limits set to underwater operations and to the transfer of stores from the ships serving the rig, set by sea states. Mr. West's comments on this would be welcome.

Finally, it would be interesting to hear whether the author considered that 120 years of oceanographic investigation had provided a sufficiently sound basis for design. His own impression, after nearly 20 years as an engineer in fisheries, was that marine science would get nowhere unless it became more closely linked with exploitation, in other words, with engineering. There were some signs that this was beginning to be realized at last. If, in the past, the sort of attention had been paid to marine technology and the exploitation of the sea that seemed to be justified by this nation's history, skills and geographical location, the present operations in the North Sea might have taken place 20 years ago and, as far as the country's financial situation and usage of scientific and technical manpower were concerned, that might have been no bad thing.

Mr. W. Kohring asked whether concrete consideration had been given to building a semi-submersible which could be described as a twin-hulled submarine with a flat work deck supported upon waisted vertical extensions through the air/water surface. Such a vessel, which had been designed in Holland, would appear to have the advantages of a semi-submersible bottom supported space frame coupled with good towing characteristics, and to be eminently suitable for dynamic positioning.

Mr. G. B. Marriott said that in reading the paper he had been struck by the very wide fields of knowledge to which almost casual reference was made—such matters as meteorology, oceanography, sea-bed investigations, metallurgy, corrosion, stress analysis, dynamic loading, as well as the more striking advances in offshore drilling techniques. The boundaries of present knowledge in many spheres had been reached in this work, and the boundaries of present practice were in some cases also encroached upon.

The author had mentioned a Sedco Type 135 unit built in the United Kingdom, adding that he had not any reference to its method of fabrication. This unit was in fact built by Harland and Wolff in Belfast, on three full-length slipways, each about 150 ft in width, with a slope of about 1 in 43. This had struck him as being very clever but shipbuilders were used to building things on a slope. Special precautions were taken to minimize the launching stresses.

The three slipways were fully served by high-capacity shipbuilding cranes. These cranes had presented a complication to the erection system because it meant that the lower and diagonal bracings on the port and starboard sides had to be left out until a fairly advanced stage in the construction. During the preparations for the launch, precautions were taken to minimize the launching stresses, and principally a large temporary pontoon was placed underneath one of the principal joints in the structure and connected through to the bow pontoon which was at the uppermost part of the slipway, so that the bow pontoon would be the last one to slide off the end of the slipway.

As a result of a reassessment of primary and secondary stresses after the unit had been launched, it was decided to carry out some additional strengthening work. This comprised stiffening rings in the main horizontal lower members, strengthening and fairing off of the main joints both at low level and at high level, and the introduction of another complete bracing member between the bows pontoon and the main knuckle joint beneath the position of the drilling floor.

Measurements were being carried out of movements of *Sea Quest*, under wind and wave action. The stresses in the mooring ropes were measured and continuously recorded, and strain gauge readings were taken, over a period, at points of potentially high stress in the framing of the structure.

MR. K. BURNIP and MR. T. HARRISON, in a joint contribution, said that with regard to the various merits of wire or chain moorings, although the author stated that it was easier to determine tension in wires, it was quite feasible to measure both static and dynamic chain tensions by the use of transducers built into the roller bowstopper shafts. These, of course, had to be calibrated to take account of the lead of chain.

The chain mooring system appeared to have certain advantages over the wire system in that only the bowstopper needed to be designed to accept the "riding at anchor" strains, whereas with wire winches, apart from the storage requirements of the barrel, the barrel frames and shafting had to be designed to accept these extreme loads. This made the wire winch heavier than the chain winch in an approximate ratio of 2 to 1.

Although the total weight of equipment using chains would probably always be more than that with wire, one would have thought that the problem of extra weight would be more than balanced in that the chain could be stored well down in the vertical column.

These points indicated certain advantages for a chain system. Did the author consider that, from an overall point of view, the more limited movement obtained with wires when endeavouring to maintain the drilling outfit on location, outweighed these considerations?

MR. A. O. BELL said that, as a consequence of the intensive exploration work in the North Sea, a number of papers on the operation of drilling rigs had been presented to the learned Institutions. Unfortunately their treatment had tended to be rather generalized and structural, and naval architectural problems had been dealt with somewhat superficially.

Outside the oil industry technical data on the service performance of semi-submersibles was particularly difficult to come by. The present paper provided much needed information on such important matters as roll, pitch, heave and surge motions, requirements of mooring systems and dynamic stability. Presumably the highly competitive conditions in the oil industry had prevented information of this kind being made available hitherto, because of its commercial value. He hoped that this paper would signal a period in which a freer exchange of ideas would be possible.

Having spent several weeks on board a semi-submersible rig, he could testify to the remarkably steady conditions in the floating condition as compared with an orthodox merchant-ship form. For instance, full-scale measurements made in a Beaufort 7 sea state showed the maximum roll angle to be only 0·50° double amplitude.

An important factor here was the high natural motion periods. For example, the Sedco 135 outfit had a natural roll-pitch period of about 35 seconds and a natural heave period of about 20 seconds. At the light draught adopted for a long tow the natural periods were about seven seconds and the motions were two to three times the values for the submerged conditions, but still very moderate.

He was interested in the statement that the corner columns of semi-submersibles should be compartmented both transversely and vertically, and would welcome any information the author could give on the criteria for damage stability adopted by his company.

He endorsed the remarks concerning the need for design calculations to include the computation of wave forces in the on-tow condition, since some recent full-scale measurements had indicated that this condition might result in higher stresses than in the sit-on-bottom condition, which had hitherto been regarded as the most critical as far as the stressing was concerned.

At first sight it might appear that the complexity of the structural arrangements on semi-submersibles would defy analysis; in fact, the marine engineer had no need to be overawed, since most computer bureaux now offered generalized structural analysis programmes as part of their software services. These programmes were highly refined and yet had been designed so that they might be applied by engineers without any knowledge of programming. Two programmes which were ideally suited to this type of problem were the IBM "Stress" and "Fran". Incidentally, the application of these computer programmes had indicated that serious errors in the stress calculations could result from assuming the members to be pin-jointed. Secondary bending stresses could be as high as the direct stress in the members, with the result that the stresses at the joints could be double the values indicated.

MR. C. J. JENSEN said that the author had been kind enough to mention Lloyd's Register of Shipping. One might ask what interest a ship classification society had in drilling platforms but, like ships, drilling rigs and drilling platforms were marine structures, and classification societies, with their special talents for survey, inspection and design of marine structures, had perhaps something to offer toward their successful development. As the author was aware, Lloyd's Register was interested to the extent of producing provisional Rules for the classification of offshore drilling rigs and marine stations, which it was hoped to publish some time during the year.

The primary object would be to provide a reference for designers, constructors and operators as to the requirements for classification. The accent would be on all aspects of safety, ranging from considerations of strength, with particular emphasis on detail structural connexion design through to provision for the safety of life. It would be necessary to inspect the structures regularly to ensure a feed-back of information to guide future design processes and operating techniques.

A previous speaker had mentioned that it would be desirable to know what stresses were coming on the rigs. It was agreed that it was very important to extend the knowledge of the stresses by the use of strain-gauging, or any other means available. This was what was being done to an increasing extent on ships today.

Some of the machinery, i.e. that essential to safe operation would come within the Rules, but that "non-essential to safety", such as the drilling machinery, would not be a matter of concern for classification, except only as to its safe installation on board.

The Rules would be framed on as broad lines as possible, while still providing guidance, in order not to hinder progress in any way. The people who used the Rules would want to be quite sure that there would be no tendency to hinder developments of new or existing types of rigs.

With regard to one of the main items of consideration, the strength of the structure, emphasis would be placed on the necessity to get reliable information on the loads coming on the structure and, in the provisional Rules, there would be three main steps in assessing the rig structure:

a) estimation of waves, wind and tide conditions for the rig operating area;

b) determination of wave, wind and tide loading on the various rig members;

c) structural analysis.

For the purpose under item a), a complete study would be made to assess the wave, wind and tide conditions. The design wave would be based on the probability of extreme conditions giving rise to maximum wave heights.

For item b), the wave loading on the member would be determined by assuming that the load was made up of two parts, first, a drag component related to the water particle velocities and, second, an inertial component related to the water particle acceleration. To facilitate the calculation of wave loads for the many wave conditions which it was necessary to investigate, the society had written a computer programme for its new IBM 360 computer.

As to item c), a previous speaker had already mentioned structural analysis by the use of special IBM computer programmes and Lloyd's Register's experience confirmed that "Stress" and "Fran" were very well suited for rig analysis.

The Rules would include periodical survey requirements to ensure that the structure did not deteriorate in service to the extent of rendering it unsafe. In a way, a drilling rig was very much like a ship in this respect and it was necessary to start off from the same basis—that periodical surveys were necessary. They were perhaps not so easily carried out as on a ship; they had to be done without interrupting the drilling operations. There could be annual surveys of various parts in rotation, so that the complete structure could be examined once every four or five years, and at the end of the fourth or fifth year possibly the rig could be taken out of service sufficiently long to give it a special survey. It would be interesting to hear what the author had to say about this.

A point of importance on ships, which would also apply to drilling rigs, was the need for attention to structural detail, not only in design but in construction. There was a feeling that one had to live with the nuisance of fatigue cracks that frequently occurred in ships. Lloyd's Register tried to minimize these by attention to design features and to prevent their propagation by using notch-tough material. There were great rewards to be gained by very careful attention to detail.

MR. A. F. WARNER said that as this was a very comprehensive paper it was perhaps unfair to suggest that some aspects had been given little attention.

The author stated that living quarters required a high standard of finish, but did not mention protection from fire. One of the dangers with any oil search operation was the risk of fire, and it was possible for submarine wellheads to be damaged, for oil and gas to come to the surface and, on occasions, to be ignited. Were refuges from fire provided on rigs?

Although employed by the Board of Trade, stability after damage was not the speaker's special subject, but it seemed to him that too much compartmentation of corner columns should be avoided. A practical proposition might be to follow the practice used in some floating docks—to fit a safety deck, or maybe two. One safety deck could be arranged above the level of possible damage by tugs, so that the rig could float upright even with all spaces below flooded, and another safety deck might be fitted 30 feet or so below the working waterline. Spaces between the safety decks, if not filled with buoyant foamed plastic, should be interconnected by large pipes through the cross-bracings, and so provide a passive system of counter flooding. Similar systems were fitted in some passenger ships to prevent large angles of heel after damage.

Had the "shocking awakenings" through increased weight been experienced in rigs built in one country rather than others? It was almost traditional in some United Kingdom shipyards to employ very small design teams and, because they were so small, some teams were forced to work by approximate methods when rapid weight estimates were required. He wondered whether surprises had been experienced in Japan, where design teams tended to be larger.

Correspondence

MR. H. L. DOVE, M.B.E. wrote that the author after pointing out that the whole economic value of the floating rig depended on the efficiency of the mooring system, then unfortunately glossed over these aspects and appeared merely to pay them lip service. This was disappointing after the really interesting earlier sections.

The diagrams in Fig. 13 purported to show the difference between the motions of a normal ship-shaped rig and the modern semi-submersible, or modern transparent rig as it was often called. There seemed no reasonable basis for comparing forms of such dissimilar displacement, unless the surface rig really needed to be that much larger to do the same job. If, however, the ships were compared at 12 110 tons displacement, it would be expected that the dotted curve would be lowered by at least thirty per cent. A more serious criticism arose from the very nature of the two designs. The ship-shaped rig had a large water plane and a full profile, while the semi-submersible had a small water plane and an open profile. The effect of this difference was that a passing wave on a ship-shaped rig produced a changing pattern of very high buoyancy forces along the length of the hull. This caused large vertical accelerations and hence large displacements, i.e. heave, pitch and roll, whilst the vertical buoyancy forces on the semi-submersible would be correspondingly smaller and the motion considerably less. This aspect was, however, merely the effect due to a static wave profile. The dynamic effect was also large and the comparison must then be on the basis of damped natural periods, because, at the resonant period of encounter, the motions would be large on either type of rig. The period of the ship-shaped rig in pitch, heave and surge was shown in Fig. 13 to be about twelve seconds. The period of the semi-submersible would probably be about twenty seconds. Hence, if the full lines in Fig. 13 were extended to cover this period, they would undoubtedly rise above the dotted lines. The comparison then became very complicated. In the latter case, a wave length in the order of 2000 ft would be required for resonance. It might therefore be argued that long waves would not occur in, for example, North Sea areas. However this would be wrong. They did occur and not infrequently—although generally the height was small.

Research in naval architecture had been stimulated by a paper* to S.N.A.M.E., where it was shown that the sea surface in a confused sea was merely the summation of a series of uniform waves of various amplitudes moving in various directions. The response of the ship to this confused sea was also the sum of the responses to the individual wave trains. The whole problem was dealt with in a statistical manner to provide estimates of maximum, mean and significant motions and thus provide good criteria for the various designs.

Since this work, many advances had been made by research workers throughout the world. The original paper required the measurement of response amplitude operators on models of the ships concerned over a range of frequency of

*St. Denis, M. and Pierson, Jr., W. J. 1953. "On the Motions of Ships in Confused Seas". *Trans. S.N.A.M.E.*, Vol. 61, p. 280.

encounter covering sea conditions likely to obtain, i.e.: $\frac{\theta}{h}, \frac{\phi}{h}, \frac{H}{h}, \frac{S}{h}$; where h, θ, ϕ, H and S were respectively wave height, angle of roll, angle of pitch, heave and surge. The theory also required the accumulation of data for the determination of energy spectra in random seas in certain sea areas. For example, North and South Atlantic, North and South Pacific, Indian Ocean, North Sea and so on. It was then required that the ordinates of the energy spectra be multiplied by the ordinates of the response operators at the same frequency of encounter, allowing also for tidal velocities, to give the energy response spectra from which the maximum significant and mean amplitudes of the various motions might be assessed. This method provided the only reasonable approach to this very difficult problem of motions in a seaway.

The first requirement for holding the rig in position, or at least within a small distance of one position, was that the anchors should hold with insignificant dragging. Hence the first requirement for an anchor was that it should easily and quickly penetrate the sea bed and maintain the required pull. The most efficient anchor in the world so far, designed specifically for this purpose, was the British Admiralty's permanent mooring anchor known as A.M.12 (Admiralty Mooring type 12). This anchor would hold a force equal to 14 times the anchor weight without dragging, and 25 times the anchor weight at a very slow speed of drag. No other anchor could equal this by a wide margin. Details of many of the proprietary types of anchor and their holding pulls were given in papers in 1950† and in 1960‡.

The next item to be considered was the cable and here it was important to provide a factor of safety, i.e. breaking load/working load = 3. The most important factor was that the cable must be horizontal at the point where it met the anchor under maximum load conditions. This decision would also determine the minimum length of cable required. The cable must then provide sufficient resiliance to absorb the stored energy in the rig due to wind, wave and tide forces, and here

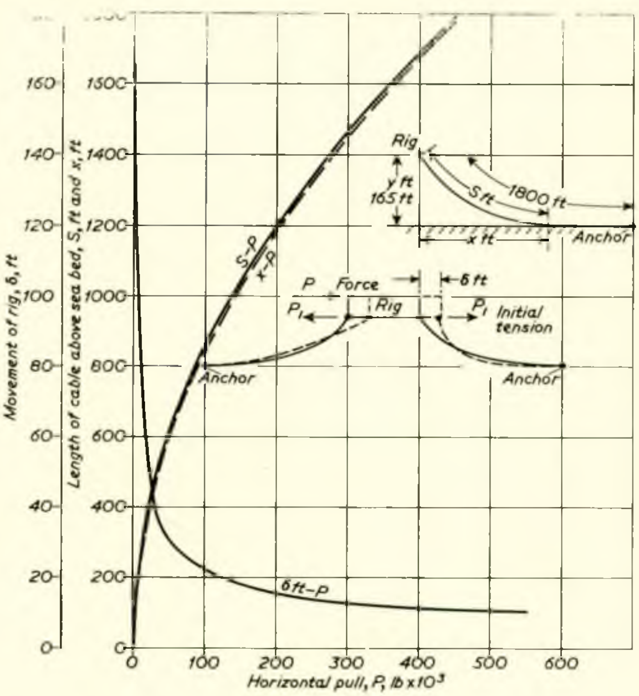

FIG. 22—*Movement of rig—Various horizontal forces acting in cable*

†Dove, H. L. 1950. "Investigations on Model Anchors". *Trans. I.N.A.*, Vol. 92, p. 351.
‡Dove, H. L. and Ferris, G. S. 1960. "Development of Anchors". *Trans R.I.N.A.*, Vol. 102, p. 535.

he must disagree with author, the most efficient way to do this was with a heavy cable and not a wire rope. In order to maintain the rig within the allowable margin of movement, some pre-tensioning of the cable would be necessary. Fig. 22 gave the movement of a particular rig under the action of various horizontal forces acting in the cable. These were actual results in a particular mooring case off the British coast. It was found that the maximum force in the cable was 300 000 lb. Assuming no pre-tensioning, the rig could move from its central position by as much as 167 ft. With pre-tensions of 25 000 lb, 50 000 lb and 100 000 lb, this movement could be restricted to 33 ft, 12 ft and 10 ft respectively. Hence it was important that the pre-tensioning be carefully and previously assessed in order to restrict the movement to within its allowable maximum in each case.

Many rigs fitted automatic tensioning devices. These could upset the whole value of the mooring and should be avoided—provided that an efficient and tested mooring had been laid.

MR. D. FAULKNER, Wh.Sc., commented, in a written contribution, that any good design must include reference to service experience so that the lessons learned might be incorporated in future designs. Although it was clear from the paper that this feed-back had taken place for structural performance, it would be helpful if the author could outline some of the lessons learnt to date. This would be particularly valuable in view of what appeared to the outside observer to have been a fairly high accident rate by usual commercial and engineering standards.

Where failures had occurred was it possible to say what proportion had been ductile (including any form of plastic instability), fatigue or brittle fracture? What proportion of failures had been due to misuse or mal-operation of the type that it would have been unduly restrictive and unnecessary to cater for by design?

Like ships, offshore drilling rigs were subject to loads whose values could not be determined with precision, but in some cases a careful study of the damage circumstances might reveal helpful data regarding loads. Could the author please outline to what extent this had been carried out and what had been some of the important lessons learned?

MR. K. V. TAYLOR, B.Sc. (Member) wrote that in the past few years, the British Ship Research Association had been involved in various marine platform projects and in several of these the builders had been concerned with the launching process. In these instances some assistance had been given to enable data to be obtained for future use and to verify predicted behaviour.

From the technical aspect, one of the most interesting was *Ocean Prince*, full details of which had recently been given in a paper by P. G. Hodgkinson to the North East Coast Institution of Engineers and Shipbuilders and which was similar to the Staflo discussed in the paper. The rig was a semi-submersible with four main buoyancy chambers in the form of four parallel cylinders. The two outer ones were approximately 335 ft, some 130 ft longer than the two inner cylinders. During launching, because of this difference in length, the inner chambers would leave the way ends causing the loads and moments to be transferred to the two remaining cylinders. Stress calculations had been carried out by the yard but, in view of the unusual nature of the structure, B.S.R.A. undertook to check the validity of the calculations by drain measurements during the launch.

Standard procedures had been used for the launching calculations with due awareness that the behaviour of four long cylinders entering the water could possibly be considerably different from the orthodox ship-shape form. For a conventional ship it was seldom necessary to consider the effect of bending moment during a launch, since the induced stresses in the main hull structure were normally of the order of one ton/in². In the case of the rig, however, there was considerable doubt as to the effectiveness of the top structure to resist the longitudinal bending and, with only the bottom cylinders to oppose the moment arising from the effects of buoyancy and weight, the stresses could be large particularly at the point where the centre caissons left the way ends. The calculations, assuming no contribution from the lop structure indicated a stress of 7·0 tons/in^2 although it was felt that this figure was unduly pessimistic. Dynamic and hydro-dynamic effects on the other hand might well increase the stress and it was most desirable to verify the computed stress by measurement.

Twelve 100-in strain gauges were used—seven located over the length of the "forward" half of the starboard outer caisson and one on each of the inner two caissons. Time and distance information were also recorded by means of two wire wound drums. All these data were recorded continuously throughout the launch.

The strain measurements showed that the maximum stress occurred in the outer caissons and was 3·0 tons/in^2 compressive as against the calculated stress of 7·0 tons/in^2. From this result it was evident that the upper structure was playing a considerable part in absorbing some of the bending moment. The total range of stress at this point was 4·05 tons/in^2. The compression phase being preceded by one of tension. The maximum occurred at a distance down the ways of 305 feet, some 50 feet after the inner caissons left the ways.

More recent work carried out by the Association on the Sedco rig described in the present paper had involved the measurement of stress in some of the main structural members while in service. This had included statistical recording on the lines of the B.S.R.A. investigation into service stresses of ships, where counts of various stress levels were related to the sea state at the time of recording.

Dr. J. Rorke (Member) wrote that the appearance of drilling outfits in the North Sea had brought home to engineers in the United Kingdom, the immense difficulties associated with the winning of oil and gas offshore. To the layman, drilling from a floating vessel seemed a highly improbable operation—when it was performed in the North Sea it became one of the wonders of the age.

The supply of men and equipment to the drilling outfit was also a hazardous operation, involving the use of helicopters and offshore supply vessels, a new species in British home waters.

In the case of supply vessels, large amplitudes of motion, in all six degrees of freedom, whilst lying alongside a bottom supported platform or a semi-submersible, was extremely undesirable. Not the least of these motions was roll, where resonance at natural roll periods of say 5 to 15 seconds, resulted in very large roll amplitudes.

Roll resonance could be avoided by the use of stabilizers of the fluid transfer type, either "passive" or "passive controlled". Both these systems used the residual roll of the vessel to move the stabilizing fluid across the ship, the transfer of mass providing the stabilizing moment. In both the passive and the passive controlled systems, the basic effectiveness of the system was dependent on the mass of fluid transferred. In the passive controlled system, an arrangement of valves situated either in the cross fluid duct or in a cross air duct, controlled the phase relationship between the ship movement and the movement of the stabilizing fluid for optimum stabilization.

A well stabilized supply vessel should enable the work of supplying offshore vessels to proceed for a greater number of days per annum than would be possible with an unstabilized vessel.

For optimum roll stabilization, it was considered that an equivalent wave-slope capacity of about 4° was desirable. A 4° stabilizer would give average roll reductions of the order of 65 per cent, whereas a stabilizer having a 2° capacity would give an average roll reduction of about 40 per cent.

The wave-slope capacity of the stabilizer was computed from the equation:

$$\theta^\circ = \frac{57\cdot 3 \times \text{Mass moment of fluid transferred}}{\text{Displacement} \times \text{G.M.}}$$

The author's comments on the need for the stabilization of offshore supply vessels would be appreciated.

Author's Reply

In reply to the discussion, Mr. West said that various speakers, starting with Mr. Eddie, had commented on wind and wave measurements, the measurement of rig movements, the correlation of model tests and the actual performance measured with strain gauges. The rigs were not designed entirely by classical methods of prediction from model tests. Model tests for the most part had been used to establish the behaviour of the structure—Mr. West was speaking now of mobile structures—in order to determine its suitability for its intended duty, which was to provide a stable platform from which to drill holes in the ground. All the models made to date had really been for that purpose. A great many of these semi-submersibles, or catamarans, or submerged catamarans, like the Stenger design, were conceptions of their inventor, or of a committee, and they were tried out in models. If the behaviour looked good for drilling, the design would proceed but, when these rigs were designed, they were designed to the best of the designer's ability in an engineering manner and, if it were necessary to check on the stress estimates, special models were set up. Examples were models of the footings of the Sedco drilling outfit in order to determine the stresses between the elephant pads or pontoons and the main columns, and similar investigation had been done with some of the joints on the space frame semi-submersibles such as the Bluewater and the Staflo.

With regard to the actual stresses encountered in service, a start had been made to place strain gauges on some platforms in the endeavour to build up some actual history of what was happening. Thus far it had not been possible to measure in extreme conditions. Perhaps fortunately, some of these outfits had not had to meet their design conditions, so one had not found how close or how far off they were. There was as much a belief that they were conservative in some of their assumptions as that they were unduly optimistic. It had certainly been noted that it was quite unusual to have a run of outfits all to the same design. They might be sisters, but there were a few stepfathers creeping in now and again.

The loads on the mooring ropes (Fig. 18) were calculated; this was the theoretical performance deduced from various computer programmes set up for the purpose. The mooring lines on a floating outfit were monitored continuously, and in most cases were recorded during extremely rough weather; he had not seen very many examples from actual measurement and considered that commercial competitive secrecy would, for some little while, prevent too easy disclosure. Another reason could be that the industry was so loaded with work that it was difficult for the engineers, and there were relatively few, to devote sufficient time to the preparation of technical papers. On resonance, they were quite concerned, not only for the semi-submersible but also for the fixed platforms, or for those requiring bottom support. There were certain outfits in existence today which would be perfectly happy in the North Sea, which would be less happy off Nigeria, say, and much less happy a little further south. He had mentioned that there was no general solution to this and that there was not really a "go anywhere, do anything" rig. One did the best possible with what one happened to have, with a very, very heavy investment. Certainly rigs were taken around the world but their behaviour, even that of semi-submersibles, could get a little lively in some parts of the world.

It had been thought for some time that the economical change-over between bottom support outfits and floating outfits would be of the order of 250 ft water depth. Maybe the economical change-over point was around 300 ft. It seemed that every semi-submersible that came out cost half a million pounds more than the previous one and there was a mass of reasons why it was necessary to spend this extra money to achieve one thing and another, but with this happening the two curves were beginning to chase each other. What really intrigued him was that, in the North Sea, under the general weather conditions, it certainly appeared from very recent studies, that a leg type outfit, a self-elevating barge, was very likely to get extremely close to its natural period in about 250 ft of water. This was being looked at rather closely.

He was very grateful for the comments on the design study for a trawl winch with the cable stored in the hull. The design of these offshore outfits was a very, very new art—it was not a science yet. Such was the stress to produce them, to get them out, and so long was the gestation period, that most designers had taken what was readily available. However, no two outfits came out the same and, every three years or so, another generation of mobile drilling outfits would be seen and there would be all these different improvements coming along.

There were very severe limits to the transfer of stores and personnel in bad weather. Various studies had been made of the logistics of supply of these outfits and it was almost impossible to get away from the fact that they must be designed for something of the order of 2000 tons variable loading, equivalent to some 20 or 30 days supply.

It was found necessary to have material supply and transfer of personnel both by sea and by air. The original conception was that everything would be done by sea and the air would be used for rapid evacuation of a wounded person, or a person suffering from an accident, or for visits of management who did not have quite enough time to spend 12 hours out and back on a noisy and perhaps uncomfortable supply boat. Nevertheless it was found necessary to have both and they cost a very great deal of money. There were roughly 4500 dollars a day tied up in boats and helicopters to supply an offshore rig. It would, of course, almost be possible to supply two rigs in the same area, with that required in any case for one rig. All ways of transferring stores had been examined, even the idea of submarines coming in underneath the submersible and latching on to it; this perhaps seemed an invention of Hollywood or of James Bond. They had tried various arrangements of cranes and swing lines on to the platform, but the right answer had not come up yet. In some parts of the world they had even tried hovercraft to see what could be done in that way. Unfortunately, as they came from the aircraft industry rather than the shipbuilding industry they were of very light construction and there was the real danger that a hovercraft could beat itself to death against the legs of the platform. There were considerable difficulties militating against the use of hovercraft.

He completely agreed that there was a very great deal more oceanographic investigation to be done. What was needed was the greatest possible attention from some of the very best engineering brains.

The reason for not drilling in the North Sea 20 years ago was not really that there was not all this information available. They had no idea there was likely to be "High Speed Gas" then. It really came about from the gas discoveries in North Holland. This provided the clue that there may well be something under the North Sea. The idea that there might be something in Holland went back to a time before the Second World War, when there was a world petroleum conference. It was held in 1937 or 1938 at The Hague and there was a small drilling rig in the grounds of the conference building. On one occasion while they were making holes with it, to their enormous embarrassment, they had struck oil.

The geological side of the industry would, quite rightly retort that it was only the great advance in seismic techniques that had made possible exploration activity over large areas of Northern Europe and, indeed, over the North Sea; only in fairly recent times had the ability been developed to interpret and estimate from such seismic records.

Consideration had been given to the building of a semi-submersible with two submarine torpedoes. The only example of this, which got very far in the design stage, was that for the Mohole which essentially was just two submarine torpedoes and a space frame on top. An excellent paper on the drilling outfit for the Mohole project was read by Alan C. McClure* to the Society of Naval Architects and Marine Engineers.

There was another design, the Stenger, which was a submarine catamaran, with two large torpedoes submerged to 50 ft draught, joined to the working deck by solid walls. The intent here was to produce a stable high-speed vessel. His company was quite interested in this but were not so sure that it would necessarily give a stable drilling platform unless it would combine dynamic stationing in which case it could be orientated into the prevailing weather. Even then there were some parts of the world where the weather gave conflicting wind, wave and current.

Nigeria was a perfect example of that.

There had been mention of the wide range of studies brought out in the paper. They were right up to the boundaries of present practice and present knowledge; in some ways they were beyond it. The petroleum industry was an adventurous industry, a romantic one—that was why he had joined it. Those in it were driven by their own desires, their own consciences, as much as by the competition of others. They did not know everything about the design of these outfits and how they behaved—very far from it.

He had heard with great interest the story of how the Sedco was built and launched in Belfast.

The points made by Mr. Burnip and Mr. Harrison in their joint contribution were well taken. It was quite feasible to measure the tensions in a chain mooring system. The feeling was that it was somewhat easier to measure with a wire system. The first matter of importance was the performance of these outfits for their intended duty of drilling holes, so they had to be kept as close above the well as possible. There was considerable concern about the distribution of weight and it was a very good idea (coming back to the design of trawl winch that Mr. Eddie mentioned) to have a look and see if it were not possible to get the mass of the wire down in a locker somewhere, so as to be able to have a very much smaller winch up top, on deck.

He had intended, in the paper, quite deliberately to say something about the technical aspects of drilling in the oceans of the world. There had been quite a few papers produced which skipped over the subject rather lightly and he did not think that this could be kept up much longer. Papers had to be produced dealing with the involved technical aspects and it was only just getting to this, for only now did people know enough to feel confident of coming before an audience such as those present and giving facts, or even daring to give assumptions, or estimations. He would very very strongly welcome anyone else, this year or next, who would present to the learned institutions papers going beyond his own in technical content.

In considering damaged stability, the criteria set by authorities such as the U.S. Coast Guard for passenger vessels was followed, though these were not in general, specifically applicable to semi-submersible drilling outfits. Damage to two compartments near the water line at drilling and towing draught was assumed and the stability investigated therefrom. There were no criteria accepted as yet for the weather conditions under which a damaged outfit should remain stable without capsizing. It was quite unreasonable to apply the same criteria as for the undamaged condition, but how much less would be acceptable? This was still a matter for individual consideration and decision.

Some information on damage stability was given by Mr. Avery in his paper† on the Sedco 135 drilling outfit. As further indication, the portion of Fig. 17 relating to a semi-submersible was repeated with the damage stability curve drawn in (Fig. 23). In accord with what was said earlier,

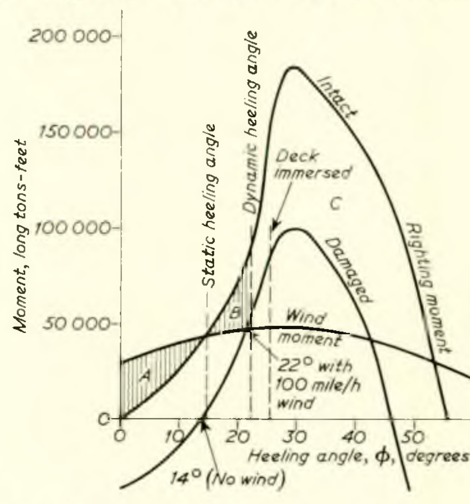

FIG. 23—*Portion of Fig. 17 relating to a semi-submersible—Damage stability curve drawn in*

this was based on two compartments, in one corner column, flooded at the drilling draught water line.

With regard to the safety of the people on board, when the roughest conditions (e.g. hurricanes) were expected it had been the practice of the industry to evacuate the platform. They were stationary and there was nothing to be done about avoiding a collision from a moving vessel. This was a fundamental reason for evacuating these platforms. Except in the direct path of a hurricane, these platforms had survived all major storms. In the roughest hurricane that anyone could dream up as a criterion, it was believed that a certain design of semi-submersible would actually start to fly. This particular design was not built.

The sresses on tow of those semi-submersibles with which they were familiar were very substantially higher than the stresses when sitting on the bottom; this was a very, very important condition to look at. It was the practice to submerge these outfits to some 30 or 40 ft draught, when it was anticipated that the highest weather might be encountered. It might also be expedient, if far enough from the shore, even to let

* McClure, A. C. 1965. "Development of the Project Mohole Drilling Platform". *Trans S.N.A.M.E.*, Vol. 73, p. 50.

† Avery, R. G. S. 1967. "Offshore Drilling with Particular Reference to the North Sea and the *Sea Quest*". Institution of Mechanical Engineers—Thomas Lowe Gray Lecture, 25th January.

them free for a bit, or cast them adrift completely from the tow and pick them up later. This had been done.

His company welcomed very strongly the work being done in this country by Lloyd's Register of Shipping and subscribed to it with all the engineering knowledge they could possibly bring to the subject. They already leaned very heavily on Lloyd's Register for their services in various respects, but did not wish to lean on them in regard to the design of drilling outfits. The industry was quite willing to stand up and take it as an industry, as would his own company in the designs it produced, but they very strongly supported the idea of producing codes of safe practice or of safe design, provided that the codes (as Mr. Jensen inferred) did not become unduly restrictive on development. He felt sure they would not.

Mr. Jensen had mentioned how important it was to make a complete survey of the expectations of weather and tide in any area. This was of fundamental importance. There was one area in the world where the engineers had started with a criteria of 55 ft wave and were very quickly up to 60 or 65 ft, and the very latest position was that after a great deal more study they had come up with a 75 ft wave as a criterion. This might be verging a little on the ultra-conservative. It was a temptation which might be inherent in all of us—to pile ignorance factor upon ignorance factor, and it was up to the leaders of a department, the chief engineers and the chief designers, to keep this in check.

Mr. West had made no mention of the safety of the lives of the crew; this was quite deliberate. The paper was intended to cover design and construction and too many chapters led to generalities. The safety of the crew was, only naturally, very much the concern of the operator and the designer. So far as practicable, the codes of safe practice of the societies, the U.S. Coastguard and the like, were followed in regard to the fire-fighting equipment and the safety equipment provided. It was, however, not at all certain that one could take an ordinary lifeboat and launch it from one of these semi-submersibles and, at the moment, various survival capsules were being investigated. Typically these were rather large reinforced epoxy-resin fibre-glass "flying saucers" into which some 20 of the crew could get, or there might be several of these balls. They would get in there and strap themselves in and then down it would go at a controlled speed. Several had been tried out and, of course, sometimes people come out with their hair standing on end, but they were a success and a great deal more sure than a conventional lifeboat.

He did not believe it would be possible to go to the living quarters of one of these outfits and take refuge from a well-fire. There was so much energy coming out of a burning oil well that there was absolutely nothing that could be done to insulate the living quarters from the heat. The only answer was an evacuation scheme; it should be made clear that a blow-out from a well was a very remote occurrence. These things were almost always due to some human error. The answer, if anything went very slightly wrong, was to do the best to keep it under control and, if there were any sign of its getting out of control, it was best to stand off and think about it and arrange how to come back and fight to regain control.

He was very grateful for the comments on the high and low safety decks. To the best of his knowledge this system was not incorporated in any of the semi-submersible designs yet, but certainly the next generation of semi-submersibles would have watertight top decks, arranged as a streamlined pontoon, adding enormously to the reserve buoyancy of these outfits. Designers had done their best to streamline the waterline and below, and the next generation should see all the top decks streamlined as well. The "horrible surprises" due to excess weight had come about in most countries and he stood by what was written in the paper. He believed it was just lack of experience and ignorance of what these things were like and where the weight increases were likely to arise. However, it could well be argued that it was also due to design teams being inadequate in numbers.

He was grateful for the contribution by Mr. Taylor and the detail of the launching of the *Ocean Prince*. It was quite important to appreciate the different launching behaviour of a semi-submersible compared with that of a vessel and high stresses in the top decks, or top members of the side trusses, could easily be attained.

In answer to the observations of Dr. Rorke, he believed that stabilization of offshore supply vessels could be important and necessary. Experience in the North Sea was proving that conditions were so much worse than in the old traditional offshore area the U.S. Gulf Coast, that complete re-thinking of supply vessel design might be needed. One drilling contractor recently remarked that the U.K. North Sea area seemed to have hurricanes almost every week, though they were not so described. In a study on supply vessels, their stability, manoeuvrability and anchoring all must be included; perhaps a stabilized and dynamic-stationed vessel would be required, maybe even a baby semi-sumbersible.

Mr. Faulkner had drawn attention to what appeared to the outside observer to have been a fairly high accident rate by usual commercial and engineering standards. Recently an article by Commander P. C. Gaucher‡, U.S. Coastguard, was published in the magazine "Offshore" of April, 1967. In this article a total of 31 significant casualties which have occurred over the past ten years was listed and causes of each casualty were summarized as follows:

Cause		*Rigs lost*
Hurricane or severe storm		8
Stability:		
1) improper ballasting, free surface excessive topside weight	5	
2) material failure	1	7
3) unknown	1	
Blow-out and fire		5
While jacking:		
1) structural leg failures	4	5
2) unexpected sinking of spuds	1	
Derrick structural failure		2
Pressure vessel failure		1
Unknown		3
	Total	31

From this tabulation it became clear that the biggest hazards for offshore drilling vessels were the operational dangers. The blow-out fire hazard was ever present during drilling. Blow-out preventer units and other safety devices became, however, more and more improved as did operating procedures and strict crew training. A typical operational danger for the self-elevating platforms occurred during the jacking-up period, either due to structural leg failure (mostly a result of unequal sharing of the load by the legs), or by unexpected sinking of spuds.

A number of losses due to storms such as hurricanes "Hilda" and "Betsy" had forced the review of design criteria for new drilling rigs.

Major casualties due to mechanical failures under conditions not exceeding these for which the unit was designed were limited to one or two cases only and from these cases little feed-back was available. However, fortunately the designer needed only small indications to learn his lesson; for example, in the author's company, the discovery of some very small fatigue cracks in the spuds of one self-elevating platform resulted in new material specifications for those parts of the structures that were subjected to cyclic loading.

Experience in designing offshore drilling ships was still very small compared to conventional naval architecture practice, while the loading, thanks to the three-dimensional character

‡ Gaucher, P. C. 1967. "Moving Drill Barges Safely" *Offshore* April.

of these units, was much more complicated. However, refined calculation techniques and the fruits of a very extensive research in the fields of structural strength were now at the disposal of the designer and the lack of experience was in this way at least partly cancelled out.

Mr. Dove's criticism on the comparison of different floating bodies was invalid when he supposed that dynamic effects were not included in these curves. The curves of Fig. 13 were, in fact, the response amplitude operators of the transfer function as used in modern ship motion study. By dividing the ordinate scales by 15, the curves of $\frac{s}{h}$, $\frac{\phi}{h}$, and $\frac{H}{h}$ were obtained. Indeed the natural period of semi-submersibles, for ship motions, was in the order of 20 to 35 seconds and they were so on purpose; not to withstand waves of these periods, but with the intention of keeping the response of the drilling unit small for the much shorter wave components of an energy spectrum as encountered in practice.

Indeed, the magnification for heave for a semi-submersible would be of the order of one for a wave period of 20 seconds.

However, such components in existing energy spectra were only a few feet high and the response of the semi-submersible would only be equal to the wave amplitude. For a wave component of ten seconds, which could carry much more energy, the response of the semi-submersible was only one-fifteenth of that of a ship-shaped vessel, resulting in a proportional decrease in heave.

Mr. Dove was perfectly right when he stated that application of the spectral analysis was a good approach. However, unfortunately, very little measured wave spectra existed for the areas in which the petroleum industry was interested. Here a broad field was still open for the oceanographers. It was said that in order to obtain the energy spectra of the ship motions, the ordinates of the energy spectra of the sea had to be multiplied by the ordinates of the response operators at the same frequency of encounter. In fact the ordinates of the energy spectrum of the sea had to be multiplied by the square of the ordinates of the response operator at the same frequency.

The performance of the AM_{12} anchor of the British Admiralty as described in Mr. Dove's paper was very interesting. When, in 1965, the author's company were in the stage of ordering anchors for their Staflo unit, they were informed by the Admiralty Experimental Works, Haslar, that the heaviest AM_{12} anchor available at that date weighed only two tons, whereas their requirement was in the order of 15 tons. They were, however, very interested in any further development in this field.

The question of anchor rope versus chain was very controversial. Extensive calculations in the author's technical department had shown that in the relative shallow waters wherein most drilling operations took place today, the catenary effect of a heavy chain was small, resulting in unacceptable high anchor forces. In these water depths, a longer wire rope, allowing much more elastic stretch than a chain, resulted in a more flexible anchor system. For the deeper water depths, however, it was accepted that chain would give better results.

In the author's department it was standard procedure to recalculate the whole anchor configuration for every new location, taking into account the local water depth, and sea, wind and current conditions. An optimum pretensioning of the anchor cables was made from the results of these calculations.

INSTITUTE ACTIVITIES

Minutes of Proceedings of the Ordinary Meeting Held at the Memorial Building on Tuesday, 14th March 1967

An Ordinary Meeting was held by the Institute on Tuesday, 14th March 1967, at 5.15 p.m., when a paper entitled "The Design and Construction of Off-shore Oil Drilling Outfits" by F. G. West, B.Sc., C.Eng., M.I.Mech.E., was presented by the author and supported by a forty minute film entitled "The Underwater Search".

The Honorary Treasurer, Mr. R. Cook, M.Sc. (Vice-President) was in the Chair and approximately 130 members and guests were present.

Seven speakers took part in the discussion which followed.

A vote of thanks to Mr. West was received with warm and prolonged applause.

The meeting ended at 7.20 p.m.

Branch Meetings

Auckland

An ordinary meeting of the Branch was held at 7.30 p.m. on Friday 25th August, 1967, in the lounge of the Marine Engineers Building, 28 Anzac Avenue, Auckland.

The Chairman of the Branch, Mr. H. Whittaker (Local Vice President) presided at the meeting which was attended by twenty members and two guests. He welcomed Mr. B. A. White (Member) who presented a lecture "Some Aspects of Shipbuilding in Germany with particular reference to the Nuclear Powered Vessel *Otto Hans* which is at present under construction at 'Deutche Werke', Kiel".

Mr. White, who is Engineer Surveyor in Aukland for the American Bureau of Shipping and Germanischer Lloyd, had recently returned from a visit to Europe where he had the opportunity of seeing progress on *Otto Hans*.

Following his presentation, two films on nuclear power development in the United Kingdom were screened.

A vote of thanks to Mr. White was proposed by Mr. Whittaker and endorsed by those present.

Pakistan

Annual Dinner

The Annual Dinner of the Institute of Marine Engineers (Pakistan Group) was held on Tuesday, 28th March 1967, in the Hotel Karachi Intercontinental, Karachi. The chief guest was Admiral A. R. Khan, H.Pk., H.J, H.Q.A., Defence Minister, Government of Parkistan. The Dinner was attended by one hundred and four members and guests from both the wings of the country, including the Director General of Ports and Shipping; the Chairman of the Karachi Port Trust; ship owners; superintending engineers of shipping companies; surveyors of Lloyd's Register of Shipping, and the Honorary Secretaries of the Institutes of Electrical and Mechanical Engineers (Parkistan Groups).

General Meeting

Mr. William R. Lennox, Senior Advisor of the Karachi Polytechnic Institute, delivered a lecture on "Quality Control" at the Merchant Navy Club on 30th May, 1967. The function was attended by seventy-five members and guests.

Vancouver

Social Event

The Vancouver Branch of the Institute is to hold a Dance and Smorgasbord at the P.N.E. Dogwood Room on Friday, 13th October 1967. All members are invited. The programme is as follows:

Cocktails and recorded music	7.00 p.m.—8.00 p.m.
Smorgasbord	8.00 p.m.—9.30 p.m.
Floor Show	9.00 p.m.—9.25 p.m.
Dancing	9.30 p.m.—11.00 p.m.
Floor Show	11.00 p.m.—11.20 p.m.
Dancing	11.20 p.m.—1.00 a.m.

Dress is optional.

Western Australia

Annual Students Night

The Branch held its Annual Students Night on Wednesday, 9th August 1967. Ninety-six members and students attended.

Mr. J. Franetovich presented his film "The Salvaging of the *Tanais*". Mr. Franetovich, who is a talented amateur camera man, was in charge of the salvage operation and before the film was shown he gave a description of the operation. The excellent visual entertainment of the film was supplemented by a commentary from Mr. Franetovich during the screening.

A cordial discussion followed which concluded when the vote of thanks was proposed by Mr. E. Morris and carried by hearty applause.

Visit to H.M.S. Hermes

On Wednesday, 30th August 1967, approximately twenty-five members of the Branch visited the aircraft carrier H.M.S. *Hermes* as the guests of Commander N. K. Bowers, R.N. (Member).

After a conducted tour of the vessel, members entertained several of the ship's engineer officers to lunch in the Chain Locker Club.

Election of Members

Elected on 19th September 1967

MEMBERS

Elections

Christopher Andrews
William Charles McLeod Dalgleish
Kenneth Dickinson
Eugene Gosh, Cdr., C.D., B.Sc., R.C.N.
John William Hamilton, Cdr., C.D., R.C.N.

Anthony Charles Maxwell Handford, Lt.Cdr., R.N.
Alan William Holmes
Menacherry Paul Joseph Lt.Cdr., I.N.
Lars Gustaf Adolf Langenskiold, Dipl. Ing.
Joseph Raymond Mullard
Charles Alan Nixon
Horace Walter Polhill, Eng. Lt. Cdr., R.N.
Wardill Murray Potts
Trevor Royle Shaw, Cdr., R.N.
Douglas Robert Glen Smith, B.Sc.
Alexander James Towers, Cdr., R.N.
Nicolaas Frans van Dee
Ian Taylor Young, B.Sc. (Hons)

Transferred to Member from Associate Member
Afsar Ahmed Khan Afridi
George Baldwin
Kenneth Benjamin Clare Beale
Ronald William Bridgeman
Owen Walter Dumpleton
Harry Edwin Hunt
Balbir Singh Karwal
Richard Peter McKechnie
Harold John Miller, B.Sc.
William Stephen Mockett

Transferred to Member from Associate
Alfred Edward Deeble
Gerald Proctor

Transferred to Member from Graduate
Minas Vardavas, M.Sc.

ASSOCIATE MEMBERS
Elections
Michael Boyden
Derek Frederick Buttery
David John Clyde
Kenneth John Cross
Anand Kumar Dixit
Peter Grant Fabian, B.Sc.
Clive Ferrier, B.Sc.
Oswald Galbraith
Frederick John Stewart Gilbert
Frank Hagon
Jal Shawakshaw Hansotia
Hassan Mahmood Kidwai, Lieut., P.N.
John Goltermann Lassen
Brian Henry John Laver, Lieut., S.A.N., B.Sc.
James Michael Lawler
Michael John Lennon
Ian Charles McIver
Donald Ewen Maclean
Cecil Douglas Martin, Eng. Lt., R.N.
Leslie Joseph Frank Mendoza
George Mergoupis
Henry Lucien Monasterolo
Alexander Pantazidis, B.Sc.
Roger John Pedrick
John Keith Phelps
Victor John Pinner
Malcolm Robertson
John Lovell Shipp, Eng. Lieut., R.N.Z.N.
Barry Smith
Derek Smith, Eng. Lieut., R.N.
Kenneth Frank Stubbs, Eng. Lieut., R.N.
Neil McLeod Sutherland, Lieut. (LD) C.D., R.C.N.
To Yung Kan, B.Sc.
David Charles Utting
Patrick Neil Waller
Leslie John Wilkinson, Eng. Lieut., R.N.
Frederick George Vincent Wright

Transferred to Associate Member from Associate
Leslie Church
Shivashankar Srinivas Karnad, Lieut., I.N.
Walter Gordon Richards
Joseph Whiteside, Eng. Lieut., R.N.
Alexander Renfrew Young, B.Sc. (Hons)

Transferred to Associate Member from Graduate
Michael John Dee
Kenneth Edward Hart
Robert George Herkess
John Lawson Hill
Anthony John Humphreys, B.Sc.
David Kenneth Martyn
James William Park
Derek Standon Pitt
William Alexander Kennedy Ritchie
Peter James Strelley, Lieut., R.N.
Alistair Peter Charles Taylor
Michael Whelan
David Whitehead
Alan Frank Wilde

ASSOCIATES
Elections
John Talbot Bell
Charles Anthony Brindle
Alaetdin Burhan
Ean James Burns
Charles William Hepworth Collings
John Bowman Connor
John Charles Couch, M.Sc.
Fung Wah
Keith Marsden Gamage
John Philip Hearson
Philip E. Heden
Evan Maldwyn Rhys Hopkins
Peter John Hussey
Matthew Alexander Johnson
Anis Alam Khan
Angus Neil MacInnes
Cid Minuchihr Monrufet
K. Viswanathan Nair, Sub. Lieut., (SD) (ME), I.N.
Norman John Parker, D.S.C.
John Brown Paterson
Kenneth Tarrant Rouse
William Shaw
Tamotsu Takaya
Robert John Wilson

Transferred to Associate from Graduate
Desmond Charles White

Transferred to Associate from Student
Richard Hugh Pearce

Transferred to Associate from Probationer Student
Peter Dunderdale

GRADUATES
Elections
John Owen Banks
Namdar Khan Bozai
John Peter Bullard, Lieut., B.Sc. (Hons), R.N.
Chan Nai Chung, B.Sc. (Hons)
John Collier
Raymond Davis
Michael James Davison
Keith Frederick Fielder
Peter Ernest Harvey
Geoffrey Michael Healy
Barry Charles Ingham

William Douglas Kerr
William Gerard McConachie
Richard Jeremy Paul Mead
Ramesh Chandra Pandey
Anthony Cyril Rojas
Barrie Raymond Rolfe

Transferred to Graduate from Student
Solomon Oladejo Alabi
Philip Davies
Vincent Mercer Holt
Harold Graham Young Lincoln
Frederick Brian Longstaff
Iain James Macdonald
Kenneth John Maynard

Transferred to Graduate from Probationer Student
John Michael Brewster
Clive Peter Flegg
Christopher Robin Handby
Mervyn Dennis Palmer
John Parker

STUDENTS
Elections
Paul Anthony Agius
David Richard Beeston
Robert Lee Bracegirdle
Roger Clifford Evans
Albert Gatt
William Arthur Thomas Goad
Barry Michael Hunt
Raymond George McIntosh
John Wallace Patrick
Ronald Portanier
Colin Edward Taylor
James Alec Towers
Andrew Jeffrey Wight

Transferred to Student from Probationer Student
Jeremy George Moore

PROBATIONER STUDENTS
Elections
Frederick Neil Bryden
Stephen Paterson
Antony William Shaw

OBITUARY

Sir John Cockcroft, O.M., K.C.B., C.B.E., F.R.S. (Honorary Member)

An appreciation by Vice-Admiral Sir Frank Mason, K.C.B.
(President of the Institute)

In the untimely death of Sir John Cockcroft, the Institute has lost an Honorary Member of the most outstanding brilliance. The country and the world will be the poorer for the departure from the earthly scene, of this great man.

I am not qualified to speak of his great achievements in science and engineering, but I feel that it is pertinent to observe that, by training and education, he was an engineer; a fact which was of unique importance to him and to others when he went up to Cambridge at a more mature age than was usual.

I met John Cockcroft rather late in our respective careers and our ways crossed all to infrequently. What so impressed me about him was that he was always the same; kind, helpful, attentive and the possessor of that rare quality, true humility. I feel that these qualities lay at the foundation of his greatness, enabling him to win the affection and co-operation of men of many different temperaments, abilities and backgrounds. It is these qualities which enabled him to accomplish his great work and it is they which will endure and continue to be a living influence on all who had the privilege of knowing him.

A great and lovable man has passed on his way.