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Technology in Deep Ocean Drilling

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Technology in deep ocean drilling

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This paper principally discusses deep-water drilling technology for hydrocarbon exploration, employing floating vessels and marine risers (connecting the seabed to the surface). This is a more exacting technology than is required for riserless drilling for sub-seabed sampling, such as used by the *Glomar Challenger*. A floating drilling unit is subject to six degrees of freedom and offhole translation. The corresponding impact upon drilling systems is examined, as well as the risk of unplanned offhole excursions, which requires the provision of vital well pressure containing systems at seabed level. Factors involved in well design are considered, including the effect of the seawater column above the seabed in reducing subsea rock strength. The paper emphasizes the importance of personnel, environmental data, and logistics to safe, pollution-free efficient drilling, and considers future costs and technology.

1. Introduction

1.1. *The oceans and petroleum exploration*

Until the nineteenth century most people who bothered to think about it believed the oceans were bottomless; generally the few who felt there must be some form of ocean bed assumed it was flat. The first systematic collection of ocean soundings by the 1872–6 *Challenger* expedition demonstrated that in many places they were 5 km or more deep and the Marianas Trench some 7.2 km. Years later another H.M.S. *Challenger* found the deepest part of the oceans to be nearly 11 km (35940 ft).

Since 1968 the Deep Sea Drilling Project (D.S.D.P. – follower to the abandoned Mohole project) employing the *Glomar Challenger*, has achieved remarkable success in obtaining sub-oceanbed information, principally by coring, in 1.0–7.3 km (24000 ft) water depths. Scientists of many disciplines have made fascinating basic discoveries in tectonics, geology, hydrogeology, sedimentary petrology, palaeoecology, oceanic circulation and the physical properties and nature of the oceanic crust. This project employs a simple technique for penetration of the ocean bed with a coring bit. Penetration through the ocean bed is restricted because a marine riser (a system connecting the ocean bed to the surface) cannot be employed; thus no established guidance path for changing the drilling bit, and, importantly, no means of controlling geo-pressures, are available; re-entry into the same hole is consequently time-consuming and difficult.

The ocean is a subject that is interwoven with the science of petroleum, especially in exploration endeavours. Many authorities believe hydrocarbons were formed under conditions associated with the deposition of marine sediment 'source rocks'.

The search for hydrocarbons on and beyond the area of the continental shelf at 200 m water depth has been successful in several parts of the world. Development activity and discoveries rapidly followed from dry land through shallow coastal waters into the open sea as the combined stimuli of increasing energy demand, asset value of resources, the ratification in 1964 of the Geneva Convention on Continental shelf sovereign rights and the development of the emerging technology and hardware permitted. Currently there are some 550 operational mobile drilling units with over 200 being built; present utilization is almost 100%. (Mobile rigs comprise jack-ups, submersibles, semi-submersibles and ships, including 16 dynamically positioned ships, but exclude fixed platforms and some 60 tenders.)

Rig hire rates range from £22000 per day for a jack-up to £55000 for a dynamically positioned drill ship for deep water drilling, with corresponding overall operating rates of some £50000 to £100000.

The technology is still developing as economic and strategic incentives demand exploration under conditions of ever-increasing water depth, environmental difficulty and cost – with the corresponding incentives to improve safety and performance.

There are four dynamically positioned drill ships in the oil industry capable of drilling in 1800 m (6000 ft) water depth; the record is 1500 m (4920 ft) drilled in 1979. A well is planned for late 1982 in 1800 m water depth in the Mediterranean.

2. Drilling principles

2.1. *Résumé of basic requirements*

Before deep-water offshore drilling technology is discussed, a résumé of the basic principles and requirements is presented for consideration of their translation into the deep-water environment.

Historically a reciprocating 'percussion' drilling system was developed from the hand-held chisel digging methods. As the hole was deepened, the walls were consolidated or 'cased', with stone, brick, wood or metal, to prevent collapse; depths were limited. From the late eighteenth century in Europe and America (A.D. 1000 in China) the chisel bit was suspended from a springpole, which was kicked down by the crew, imparting a reciprocating pounding motion; the 'digger' became the 'driller'. Water was periodically poured into the well and debris bailed out.

Over the last 60 years the percussion method has been superseded by the 'rotary' system in which the bit is rotated from the surface by a multi-section tubular drill string – the general bit and brace principle – where a downward force is rotated and cuts, chips or scrapes the material to make progress. The radical change was to introduce fluid down the inside of the drill string to simultaneously flush the cuttings back to surface up the outside, keep the bit cool and keep the hole full of fluid to provide the hydrostatic pressure required for geopressure control.

A derrick with multi-sheave block system is employed as a simple crane with a drawworks (hoisting winch) absorbing some 2–4000 HP (1.5–3000 kW) for handling drilling loads up to 400 t. Initially animal power was used, followed by steam, diesel mechanical, diesel electric, and diesel–a.c. power with solid-state rectification.

Heavy 'drill collars' are interposed between the bit and limber drill pipe. These fulfil the functions of applying weight to the bit, ensuring that the thin-walled drill pipe is always maintained in tension, and that the hole is straight. The upper end of the string is of square or hexagonal cross section, which allows transmission of rotary torque combined with vertical travel. The driller lowers the string and applies some of the weight of the drill collars to the bit in order to make and control progress.

Fluid pumped down the drill string emerges through bit nozzles, impacting upon and

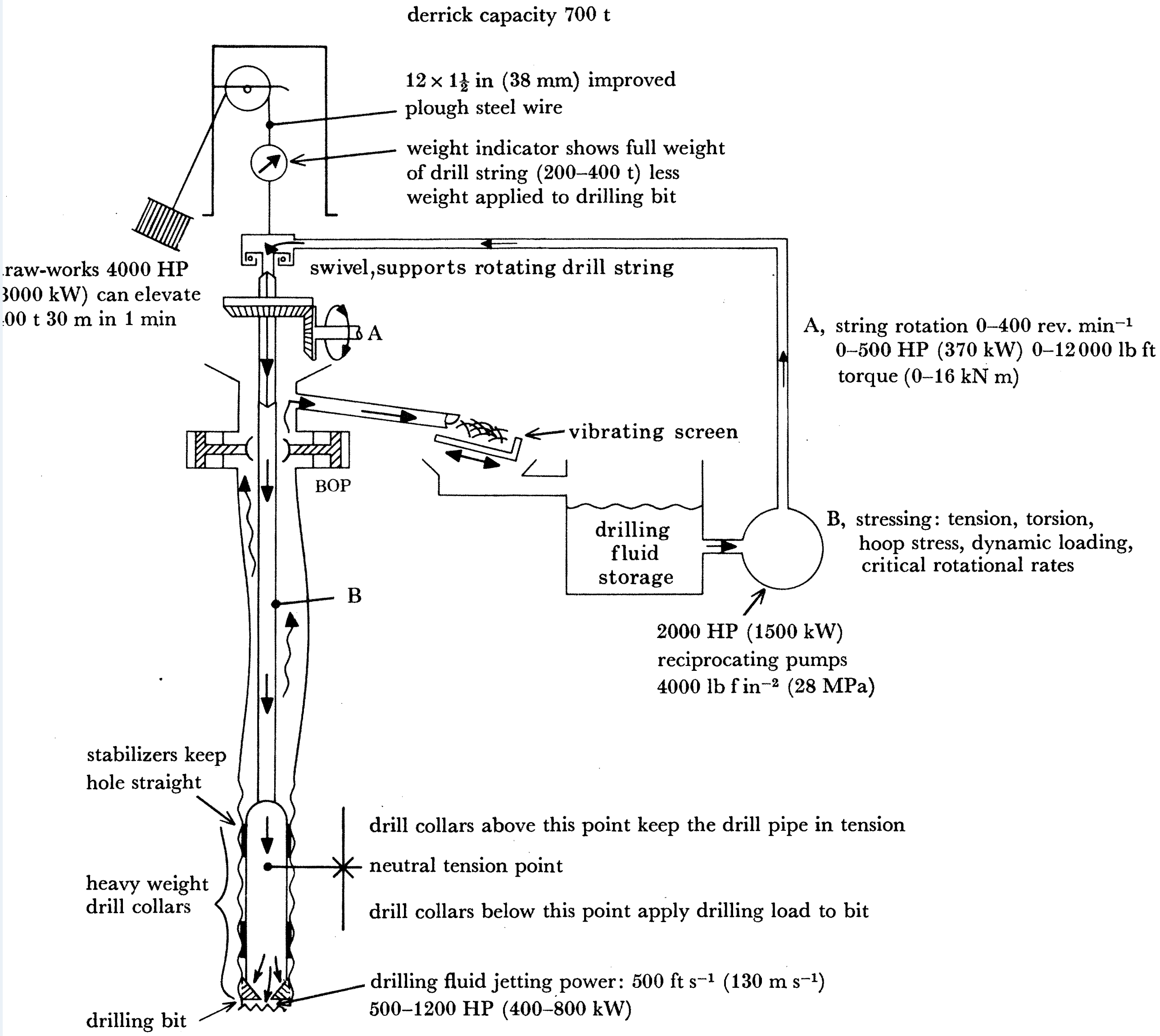

FIGURE 1. Drilling system.

scavenging the exposed rock, and continuously returning cuttings to the surface via the annulus, where they are screened; the fluid is recirculated. The preselected nozzles convert surface pumping power *ca.* 2000 HP (*ca.* 1.5 MW) at some 4000 lbf in^{-2} (28 MPa) into high-velocity fluid jets of some 500–1000 HP (*ca.* 370–750 kW), which assist or exceed the cutting performance of the bit teeth. (Nozzle size is chosen to optimize system hydraulic power at the bit and reduce system energy losses.)

The drilling fluid also performs the vital function of controlling subsurface geopressures by its hydrostatic and hydrodynamic pressures. It is carefully selected and continuously conditioned to always have the correct rheological and chemical properties to suit the depth–pressure régime and lithological–temperature condition of the formation being drilled. It is thixotropic, so that the column of cuttings (possible 5 km) will not settle when circulation is interrupted. It may have to be weighted to produce a hydrostatic pressure equivalent to 2$\frac{1}{2}$ times that of water;

or be lightened to provide a lower hydrostatic pressure than water, or converted into a non-water-based fluid to obviate damage to water-sensitive rock zones. It has to build an impervious mud cake between 1 and 2 mm thick on the sides of the borehole to prevent the expression of drilling fluid and destructive invasion of an incompetent rock formation or pollution and inhibition of a potential producing zone. The density and other properties are changed a number of times in each well.

The bit makes progress until it is necessary to add another 10 m length of drill pipe or until the bit becomes dull, when the drill string has to be pulled out and racked vertically in triple lengths in the derrick.

2.2. *Sequence of drilling a typical* (5000 m) *onshore well*

A site is prepared, water supplies made available, and some 2000 t of rig equipment and consumables moved in.

Usually a 24 in (610 mm) diameter hole would be drilled to some 300 m to allow the insertion of steel casing to line the borehole, forming an anchor for installation of control valves (blow-out preventers (BOPS)) to contain any geopressures from subsequent deeper horizons. This casing also performs the strategic functions of isolating the low-strength surface rocks from the higher-density drilling fluid needed to combat geopressures in the lower section of the hole, isolating near-surface water-bearing strata, or loss zones.

Liquid cement is pumped into the casing and subsequently displaced from the lower end to fill the annular space behind completely. A casing head is connected to the top of the casing at ground level and the BOP installed.

Drilling continues with a $17\frac{1}{2}$ in (445 mm) diameter bit to some 2000 m. By adjusting the rotational rate, pumping pressure, ‘weight on bit’, and the drilling fluid properties, the driller can obtain maximum penetration performance for the specific formation.

After the next string of casing ($13\frac{3}{8}$ in (340 mm) diameter) has been inserted and cemented, it is supported by the casing head at a predetermined tension calculated to accommodate any mechanical and thermal stress changes during subsequent drilling operations. After drilling a $12\frac{1}{4}$ in (311 mm) diameter hole to *ca.* 4000 m, $9\frac{5}{8}$ in (244 mm) casing (250 t) would be inserted, then an $8\frac{1}{2}$ in (216 mm) hole drilled, followed by 7 in (178 mm) casing.

3. EVOLUTION OF DRILLING RESOURCES

As the need for exploration moved from land, two logical developments were open: to mount an onshore drilling rig either on a fixed piled structure (or artificial island, 1925 Caspian Sea), or on a flat-topped barge with a slot cut into the hull at one end to allow the barge to move away, leaving the well intact.

3.1. *Fixed structure platforms*

The fixed piled structure principle was pioneered from 1930 for exploration and production drilling and is now generally only viable for production drilling as associated costs are disproportionate to water depth and environmental conditions.

3.2. *Tender unit*

The tender allows the use of a simple lightweight fixed structure with the drilling equipment (apart from the derrick) mounted upon a tender, which may be self-propelled and with a suitable crane to transfer the derrick, BOP, etc., onto the lightweight platform. This method has limited water depth, environmental and logistics application.

3.3. *Flat-topped barge or swamp barge*

The barge was towed along existing or dredged waterways, and on the selected location ballasted down to rest on the bottom, which was generally of soft silt; the limiting water depth was some 10–12 ft (3–$3\frac{1}{2}$ m). As deeper water requirements arose (the principal impetus was in the 1950s), one solution was to raise the level of the drilling rig above the barge deck by inserting a steel structure, increasing the capability to some 30 ft (9 m). This became known as the 'posted barge', and in effect was the origin of the 'submersible'. In 1951 the first offshore Persian Gulf discovery was made from a barge. In 1962 BP employed a similar unit for the first European offshore hydrocarbon exploration well in Lulworth Cove, Dorset.

3.4. *Submersibles*

A requirement for still greater water depths brought further empirical development of the posted barge or submersible principle. As expected when ballasting or deballasting with a high centre of gravity, it became inherently unstable; spud legs at each corner of the hull partly alleviated this problem. Many innovations, principally sponsons, sponson bottles and a simple jacking system, were developed; the sponson bottle proved to be the most viable solution. The first moveable unit was used at Lake Maracaibo in 1933.

This was the inception of the semisubmersible. Concurrently the variation employing the elementary jacking system was developed and formed the inception of the self-elevating 'jack-up' principle (although jack-up civil engineering barges had been employed in the late nineteenth century).

These developments filled the operating requirements in depths from 3 to 50 m and satisfied the oil industries' requirements for some time. During this relatively quiescent development period the jack-up concept received the greater attention.

3.5. *Jack-up units* (*self-elevating platforms*)

From the early 1950s there was an accelerating development of jack-ups. Initially grossing some 4000 t they appeared in a variety of types, configurations and multiplicities of legs; older varieties with up to 14 legs were generally replaced by units with 3, 4 or 5 legs of lattice or tubular construction. By the late 1960s the operating depth range increased to some 100 m. This is limited by a number of factors: water depth, allowance for seabed penetration (say 0.5–20 m depending on soil conditions), a minimum air gap between sea level and underside of the hull (say 20 m in the North Sea for the 100 year storm), allowance for a tide of between 1 and 4 m, for storm surge and meteorological phenomena affecting the sea level; thickness of the hull, height of the jacking mechanism and a minimum reserve above the jacks. In the North Sea, in some 100 m water depth with a hard seabed, a leg length of some 135 m (440 ft) is required.

Three distinct problems arise from leg length: their individual and collective strength as long slender columns, stability when underweigh with the legs retracted, developing a high centre of gravity, and when afloat, the inability of the legs, protruding below the barge, to respond to accelerations induced by roll and pitch.

Once elevated to a suitable height above mean sea level, drilling operations continue unhindered by all but extremely severe conditions such as hurricanes. In common with most 'mobile' units they are self-contained for drilling and supporting the whole operation and able to carry a 2500–4000 t variable deck load (VDL).

The seabed is 'extended to surface' by a 30–36 in (762–914 mm) diameter 'conductor riser' on which may be supported the weight of the casing strings, wellhead and BOP (some 500 t). An alternative system is to support these loads immediately below seabed level. Once the conductor is established, drilling virtually becomes an onshore operation.

Jacking up and down constitutes a critical manoeuvre as a 3000–8000 t mass is transferred from a floating hull to legs or vice versa; the hull responds to heave and angular motions and accordingly there is a real risk of serious leg or hull damage if legs pound on the seabed.

3.6. *Semisubmersibles*

From the early 1960s the need to drill in water depths beyond 150 m increased; it had become obvious that the jack-up concept could have a limitation of some 100 m in hostile marine environments; a floating unit independent of, and transparent to, swell and wave was therefore required.

The development of the submersible concept (1958) automatically led to the semisubmersible concept because the stabilized column was common to both. A variety of variations and configurations were built, and formed the basis of first-generation units; design was conditioned by the marine architect's interpretation of requirements to meet the near-shore relatively placid conditions. They were stable, had good motion response characteristics, and were virtually unaffected by waves and swell; performance lived up to expectations. However, all designs were difficult to construct and tow.

The second generation, in service since the early 1970s, includes the twin submarine hull design with four, six or more vertical columns between the hulls and the superstructure. In the transit mode the hulls are at the surface, and in the operating mode some 20 m below the sea surface being unaffected by wave and swell of a celerity less than 18–20 s. Principal improvements, originated for the severe North Sea conditions, have been increased structural redundancy, improved variable deck loads (1000–2500–4000 t) for logistic independence, and radically improved mooring performance. Hull shapes have changed to improve transit speed; mobility has been radically improved by making them self-propelled. Azimuth thrusters allow good manoeuvrability and can be employed to supplement the moorings. Operational water depth capability is in excess of 500 m, and one unit is dynamically positioned (absorbing some 8000 kW, or 20–30 t fuel at £6000 day). More are under construction.

Motion response is a sensitive function of size and configuration, geometry, column waterplane area and dampening or induced suppression. In nearly all designs at present, the natural frequencies of adverse motions (roll and pitch, heave, surge and sway) are kept well below the frequencies at which waves have maximum energy: resonance is avoided in all but exceptional storm conditions.

Latest regulations require that there be improved damage stability and that the superstructure be able to provide floatation, also that immersed cross-bracings be dry to permit 'in-use' inspection. Certification requirements become more demanding and expensive to implement as operations are extended to deeper and ever more hostile environments.

From the structural loading aspect vortex shedding becomes important, as does the effect of windswept entrained water striking structures in hurricane, storm or icing conditions. Mooring chain cables (even combined wire–chain cable) become increasingly heavy – for 500 m water depth some 1700 m of chain is required for each of eight or more anchors, at some 100 kg per link.

3.7. *Drill ship*

From 1953 occasional experimental efforts were made to use ship-shape hulls for stratigraphical coring and drilling. By 1964 the drill ship, as it is known today, appeared as a viable operational unit. Drilling is performed through a 20–30 ft (6–9 m) diameter access in the hull, a 'moon pool', usually at the optimum point in the hull to mitigate motions. Some early units drilled over the side, but suffered greater weather delays. Drill ships have the advantage of competitive construction costs; they can also be converted at attractive prices.

The various designs have motion characteristics that fall in a narrow spectral band and are responsive to the six degrees of freedom. Compared with semisubmersibles, more time is lost carrying out their drilling function in rough seas; in particular, roll, pitch and heave adversely affect operations. However, this disadvantage was originally offset by the greater water depth in which they can operate, greater mobility and large VDL capacity (10000 t), thus simplifying logistics.

Most of the conventionally anchored vessels are able to adjust, within limits, on their moorings to head or quarter the bow or stern into the seas. A beam sea producing rolling conditions exceeding 6–7° single amplitude disrupts drilling operations. Anchoring from a centre-well turret enables the vessel to rotate on its moorings; application of athwartship thrust from bow and stern thrusters mitigates the beam sea problems for moderate sea conditions and reduces anchoring requirements.

3.8. *Dynamically positioned drill ships*

Dynamically positioned drill ships, (DPDS's), first used in 1953, do not depend upon moorings and are able to operate in worse conditions with consequently less downtime than moored drill ships. However, considerable additional sophisticated expensive equipment and installed power is required. Of some 16 operational units (two under construction), four have a water depth capability in excess of 2000 m.

Hydrophones retractably located below the hull of the DPDS receive acoustic signals from a seabed beacon; by computer analysis of this signal, the exact position of the DPDS in relation to the well can be determined. A control loop between the computer and the ship's main propellors, and athwartship thrusters located at each end of the ship, ensures that it hunts a position within a prefixed excursion radius. Additional parameters are injected into the control loop, for example wind gust interpretation; accordingly induced off-hole displacement is anticipated and avoided. Response is usually rapid and the DPDS is held tightly on target. Current designs employ either direct-path acoustic (digital), or, where water depth permits, a taut-wire (analogue) method of detecting their surface position.

The ship's head is normally kept into the weather; gyroscopic data are fed into the control system to compensate for ship motion. The system is automatic after initial positioning. Some 6000 kW may be continuously required for position keeping, demanding a daily fuel consumption of some 15–25 t (£4500 per day). A 20000 t DPDS can retain its position to within 30 m in 2000 m water depths in 5 m significant seas. Most units are unable to operate successfully in water depths of less than 100 m because the degree of positioning needed can impose unacceptable hunting and angular deflexions to the drilling system (a sensible limit is some $2\frac{1}{2}\%$ of water depth).

The DPDS is most effective in very deep water or where a rapid move-off is essential – as in ice floe areas – or to reduce maritime risk in congested waters. The occasional drive-off situation, due to positioning system malfunction, is compensated for by an automatic disconnect system protecting the ship and seabed drilling equipment, which are mechanically linked.

The design of the vessel must allow for abrupt load changes, when transferring 250 t from the vessel to the ocean bed, by having an appropriate metacentric height and righting moment under wind-induced heel conditions.

4. DEEP-WATER DRILLING FROM A DYNAMICALLY POSITIONED DRILLING UNIT

This was a successful rapid major evolution for an innovative but rather conservative industry, where challenge is the norm. A somewhat empirical approach was enforced by circumstances: results have been eminently successful, and new generations of vessels have resulted.

4.1. *Constraints imposed by the marine environment*

The following conditions have to be considered before and during the operation

(1) persistent adverse weather in some areas, particularly continuous swell and superimposed changing currents, low sea and air temperatures with additional wind chill effect considerably below freezing point;

(2) the possibility of ice accumulation, both from precipitation and spray, affecting stability and performance;

(3) iceberg migrations;

(4) the seabed may have to be investigated before drilling for the possibility of mechanical competence for establishing the guide base and acoustic beacon and for supporting the seabed wellhead–BOP system and casing strings (some 600 t), and also to identify the presence and threat of shallow gas, or pock marks, or furrows left by growler icebergs, or deposition of rafted boulders;

(5) the logistics and transport strategy;

(6) the proximity of emergency support and rescue;

(7) the requirement to ensure safe and pollution-free efficient operations; so far pollution has been negligible in comparison with that from shipping sources.

4.2. *Recapitulation of basic drilling requirements defined in* §2

(1) Provision of an initial reference and landing point on the sea bed for commencing the well.

(2) Means to circulate drilling fluid back to surface, through the interposed water column to a moving vessel. Reducing the risk of fracturing the geological formation.

(3) The installation, and reliable means of controlling a BOP stack attached to the casing at ocean-bed level so that the well and vessel have independent security. The importance of early detection and control of the entry of formation fluids into the borehole.

(4) The need to handle expeditiously a 300 t drill string at 5000 m depths below a moving vessel.

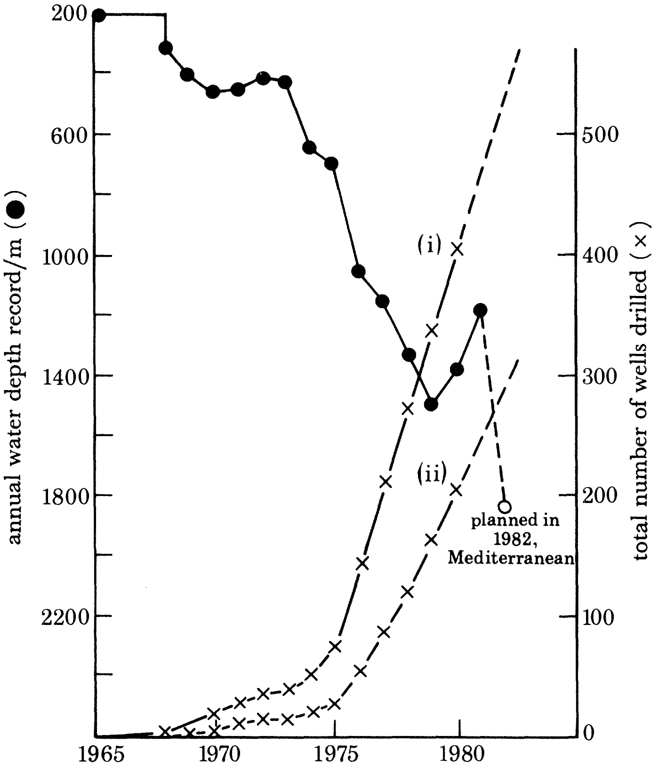

FIGURE 2. Annual maximum water depths and numbers of wells drilled in ocean depths below (i) 200 and (ii) 330 m by the petroleum industry (200 m is continental shelf depth).

(5) The requirement to rotate a 300 t drilling string at between 0 and 300 rev. min^{-1}, transmitting 12000 lbf ft (16 kN m) torque through a 0–5 km vertical shaft under cyclic bending motions induced by the moving drilling vessel.

(6) Accommodating the effect of landing a 3500 m casing string weighing up to 250 t on a rigid seabed support under 0–7 m heave conditions, and the consequences of the corresponding instant changes of equilibrium forces acting on the vessel.

These prime objectives are inclined to be obscured by the sophistication of the dynamically positioned drilling unit and the associated advanced technologies. At all times we must recognize that the drilling vessel must be free, in an emergency in only a minute or two, to move away from the borehole, which must always be left in a secure condition. Strict operations planning and management is essential so that specific operations, particularly hazardous ones, e.g. testing hydrocarbon production, are governed by the meteorological forecast and vessel status.

4.3. *Translation of basic drilling requirements into the deep-water environment*

4.3.1. *Typical sequence for starting the well*

For this illustration I am assuming a water depth of 1000 m or more and a hole depth of 4000 m. It is essential that the bit, casing or other tools can be guided back into the same hole in the ocean bed. Guidance is initially achieved by lowering a temporary guide base (TGB), weighted to some 10–20 t, onto the seabed by using the drill string with a releasing latch. When the TGB reaches the seabed the drill string is disconnected and recovered. (Moored units employ wire guide lines attached to the TGB constantly tensioned from the surface for guidance.)

The drilling bit, usually 36 in (914 mm), is guided into the TGB with a combination acoustic–television re-entry system. Since DPDS's usually operate beyond the economic 200 m commercial diving range, all operations must be accomplished from the surface, remotely controlled t.v. vehicles with limited manipulative capacity and the drilling vessel's own t.v. are normally the only aids available: expensive manned intervention units are difficult to justify.

The drilling bit would be run to a point immediately above the TGB; the combination tool would be run through the $3\frac{1}{2}$ in (90 mm) bore drill string to a point immediately below the bit. An acoustic signal indicates the position of a re-entry guide cone in the TGB in relation to the bit. Slight repositioning of the vessel compensates for current- or tide-induced displacement of the drilling vessel and drill stem.

After the target has been centred by acoustic means, the shorter-range low-light t.v. system is employed for fine guidance into the TGB guide cone. The same principle is employed for other drilling tools and the initial casing string prior to establishing a marine riser.

The hole is drilled in the conventional manner with seawater as the drilling fluid, but without return of fluid to surface, to some 100 m below the seabed. Since there is no lateral constraint on the drill string at this stage, care has to be exercised to prevent breakage of the drill string due to cyclic bending and gyrations. The drilling vessel may not be over the centre of the bore hole but will be describing an orbit around it, owing to the characteristics of the dynamic positioning system and the applied environmental forces. There is also an effect of current and tide on the exposed rotating drill string generating bending and magnus effects.

After the 36 in hole is drilled to the desired depth the hole is flushed clean with viscous drilling fluid. The first casing string (termed a conductor – usually 30 in (762 mm)) forms a key part of the subsequently installed subsea wellhead system (SSWH). We recall that the onshore operation had a wellhead and BOP installed on the casing; in this instance the wellhead is on top of the conductor at ocean-bed level. The conductor ultimately may have to support the full 600 t vertical load of all the other casing strings and the BOP stack, and simultaneously the bending loads applied by the long lever arm of the marine riser system, when the drilling unit is displaced or current drag induces a riser displacement.

A permanent guide base (PGB) is attached to the top of the 30 in conductor casing and the whole assembly is lowered on the drill string, guided and landed on the TGB with a spherical aligning surface whereby the PGB is level irrespective of the angle of the ocean bed. The conductor is cemented in position, usually by a hydrostatic balance technique. The drill string is then disconnected, either mechanically or by means of a remotely controlled hydraulically activated connector, and retrieved to the surface.

A method of establishing re-entry by employing a low mass principle has been developed for guiding the 200 t BOP system. The drill string would be guided as before, and latched into the wellhead with a low-mass (1 t) hydraulically actuated probe; the drill string itself is then used as the internal guidance for the BOP or other massive package.

4.3.2. *Means of circulating drilling fluid back to surface, avoidance of formation fracture and initial operations*

While drilling ahead after setting the conductor, it is necessary to extend the ocean-bed 'to the surface' for the following reasons:

(i) for the primary control of geopressures, including near ocean-bed methane or other diagenetic gas, by means of the hydrostatic pressure of the drilling fluid column as may be required;

(ii) the logistic incentive to conserve the relatively expensive drilling fluid, under conditions of fixed storage capacity, by recirculation;

(iii) for the return of geological samples;

(iv) to act as a repeated re-entry guide when running the drilling tools into the well;

(v) to support and protect the drill string.

For this purpose a marine riser is installed: this expensive integrated system, which has to be articulated and telescopic to allow for vessel motions, comprises a number of units each of which perform a specific function; it is one area of advanced technology where the theoretical and mechanical design and application are actively evolving for ever deeper water.

The basic system of major components, starting at the seabed, comprises the following.

(i) A hydraulically actuated connector at the lower end, remotely controlled from surface, engaging a mating hub on the top of the conductor or BOP stack.

(ii) A flexing joint to permit some 10° of omnidirectional deflexion allowing a limited off-hole translation of the drilling unit and marine riser movement. Concentrated deflexion at one point requires a replaceable wear bushing to mitigate the deleterious effects of drill-pipe rotation and reciprocation. A wide-angle unit of low fixing moment is essential. A flex joint angle indicator frequently reveals that the angle may have little relation to the mean angle of the riser with relation to the drilling unit.

(iii) An instrument package, with surface readout, may be incorporated at this point to measure quantatively bending and tension stress, deflexion angle and direction, also drilling fluid pressure, temperature, density and presence of entrained hazardous gases.

(iv) A surface-controlled large area sleeve valve to permit rapid filling or dumping the contents, for control of the well or protection against riser collapse, buckle or burst.

(v) The marine riser pipe is usually of 18$\frac{5}{8}$ in (480 mm) diameter and in 15 m lengths and equipped with manually activated connectors. The marine riser has attached to it two or three high-pressure tubes termed the kill and choke and circulating lines, usually 3–3$\frac{1}{2}$ in nominal (100 mm) and 10000 lbf in^{-2} working pressure (69 MPa); these form a continuous connection to the BOP stack and connect simultaneously when the marine riser is engaged.

(vi) An upper omnidirectional flexing joint.

(vii) A swivel to permit full tensioning with change of vessel heading.

The top section of the marine riser comprises a 15 m travel telescopic joint, the inner section is connected to the riser, and is therefore in effect anchored to the seabed. This allows for length changes due to tidal, current, barometric pressure and off-hole translation. The outer section is supported from the underside of the rig. Horizontal outlets are incorporated for the returning drilling fluid. An automatic sealing device termed a diverter is also incorporated to divert the returning drilling fluid should it contain entrained gas.

The marine riser is tensioned to prevent it slumping and buckling as currents, which may be in dissimilar directions at different depths, deflect the riser. The dense drilling fluid exacerbates the destructive bending tendency and compensating tensions up to 250 t may have to be applied by tensioners, which apply a constant load irrespective of vessel motion. Accordingly, between 4 and 12 tensioning lines are attached to the non-moving section of the telescopic joint. These are individually tensioned by an oleopneumatic unit each developing a line tension of 60 t and with a stroke of 15 m. The design and use must allow for the dynamic interaction of the components and vessel.

Tension is applied to a specific degree according to many parameters analysed by a specific computer program, of which there are two main régimes: quasi-static and dynamic (which includes water particle forces and vortex excitation). A synthesized profile of the marine riser inclination and curvature can be generated as it convolutes under the influence of vessel displacement and motion, current conditions, tensioning and shear stress distribution, the effect of the drill string and heavy drilling fluid, and other factors. It is essential to tension the riser to the minimum computed necessary, otherwise it will suffer a radically reduced fatigue life, with early failure jeopardizing the well and vessel. Programs to analyse fatigue and erosion are necessary.

A number of powerful factors interplay to determine tensioning requirements including size, wall thickness, steel grade, length, attitude, off-hole displacement of the rig, rig motions, non-uniform current profile velocities and directions over discrete intervals, seabed current (up to 4 kt (7.4 km h^{-1})), tensioning system inertia, density of the drilling fluid, type of end fixation, water particle orbital motions, and other factors.

Design requires the use of harmonic finite element analyses for determining state and dynamic stress patterns with subsequent strain-gauge instrumentation to confirm design parameters.

For marine risers in excess of 500 m length, a method of buoying the riser is incorporated. Usually the attachment of syntactic foam toroidal sections, or air-filled cans, or double-skinned tubulars where the water in the annulus is displaced with high-pressure air. This reduces axial tension stresses and tensioning requirements but at the penalty of increased drag. The weight is decreased by this additional buoyancy, but the effective mass remains or increases. Accordingly the stress distribution and forces in the riser, and also the tensioning and the surface system, generate problems – particularly when the riser is unconnected at the ocean bed.

A recoil system may have to be incorporated to suppress the broaching effect should the riser inadvertently disconnect or fail during periods of high tensioning loads. Since a ship can heave at wave or swell celerity, and a disconnected long riser system has considerable inertia, the support system is designed to apply tension but not compression.

A disconnect sequence can be automatically actuated at the BOP to sever the drill pipe and close the BOP in a disconnect emergency. Considerable attention has to be given to handling and storage of the marine riser system which is vulnerable to damage.

Figure 4 demonstrates the bursting effect imposed on a marine riser due to drilling fluid densities.

Avoidance of formation fracture. The pressure gradient below the seabed is considerably different from that experienced onshore since a section of rock with an average relative density of 2.5 has been replaced by seawater with a relative density of 1.04.

Because the geological interface begins below the rig by the amount of the water depth, the overburden and pore pressures, and also fracture gradients (intrinsic factors affecting the rock strength), are radically different from those encountered onshore. Thus the well has to be designed accordingly, with conductor and subsequent casing strings set at a correct depth for the particular water depth, rock type and well programme. Exact monitoring of existing pore pressures (by analysing rock cuttings, penetration rate, etc.) is an essential control.

A brief example shows that when continuing the borehole below the bottom of the conductor

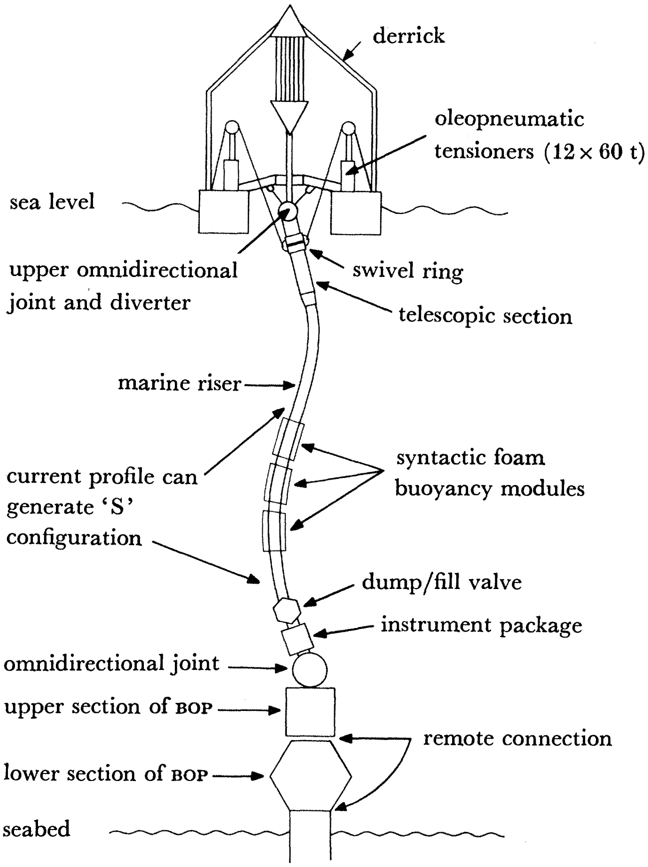

FIGURE 3. Typical marine riser system.

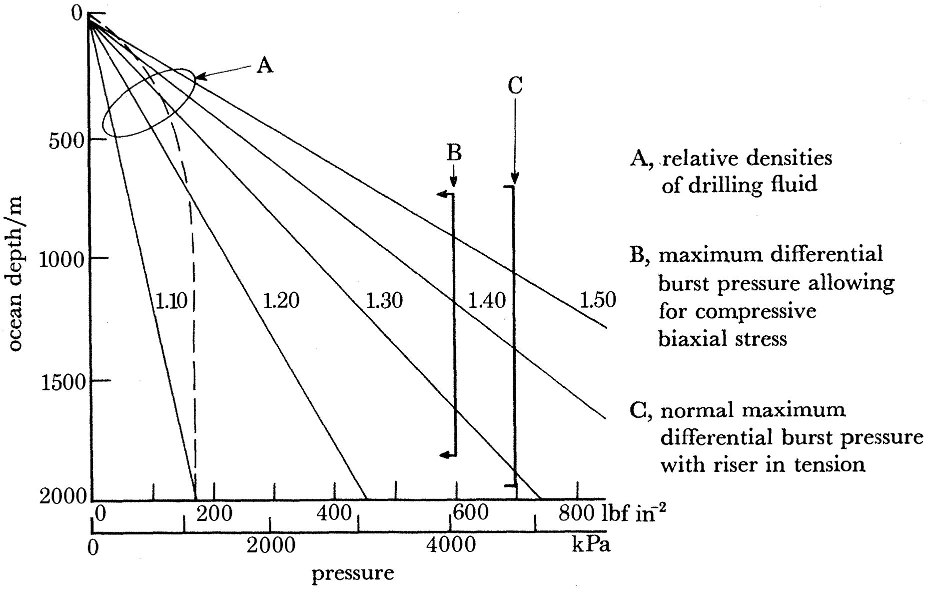

FIGURE 4. Example of drilling fluid differential pressure inside a marine riser as a function of ocean depth. The broken line shows the normal limit of the fracture strength of the seabed formation.

with a column of drilling fluid of low relative density, say 1.09, through the subsequently installed marine riser, the corresponding pressure increase, in relation to seawater (r.d. 1.04), could apply a fracturing pressure on the formation greater than its fracture resistance. The hydrodynamic pressure, due to circulation and transporting rock cuttings, further exacerbates the risk of fracture.

The effects of low-strength geological formation in combination with long marine risers containing drilling fluids of a density greater than seawater limits the additional back pressure that can be applied for well control.

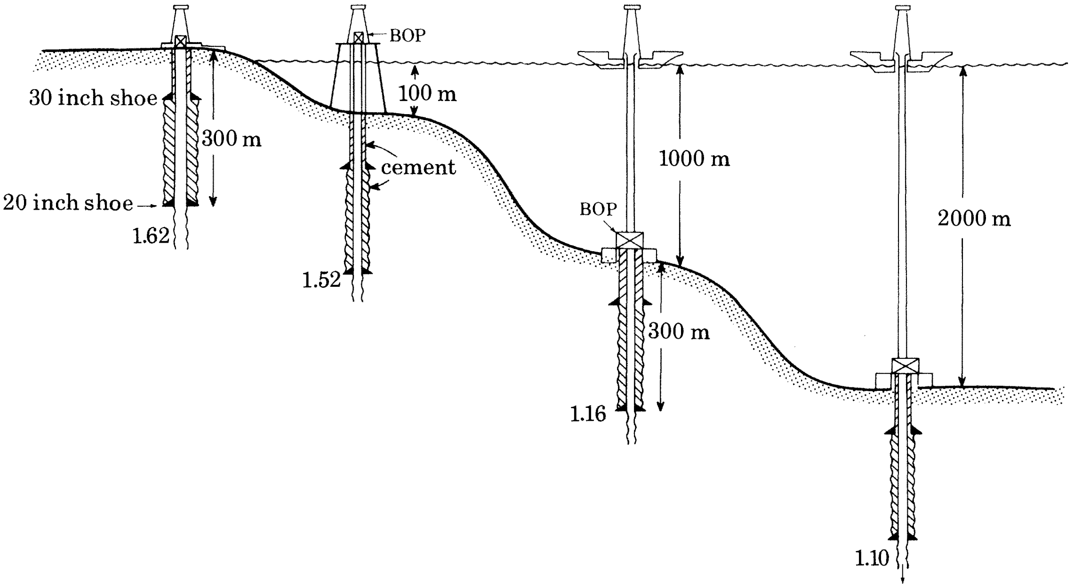

FIGURE 5. Effect of water depth on formation fracture strength at a 20 in (503 mm) shoe some 300 m below ground or seabed level. Numbers at the bottom of each well are the formation fracture resistance expressed as the maximum relative density of a static drilling fluid column. The relative density of the 'muddy' sea water in the borehole at the right is 1.09 – virtually formation fracture strength.

Initial operations. After the marine riser is installed, which is a specialized operation, it is tested by tensioning to a value beyond normal and filling with fluid; the bit is run, say $17\frac{1}{2}$ in (445 mm), and the hole drilled to some 300 m below the seabed. The hole would be under-reamed with a bit, hydraulically expanded by circulating pressure, to some 26 in (660 mm) in diameter. The marine riser would be removed for installing and cementing the 20 in (508 mm) casing, which would be supported by the conductor.

The top section of the casing would include the hub of a high-pressure connector, forming a $16\frac{3}{4}$ in (425 mm) bore wellhead body (WHB) of 10000 lbf in^{-2} (69 MPa) working pressure.

The 10000 lbf in^{-2} BOP stack would be lowered and connected to the hub on the 20 in casing, then pressure tested and the drill-pipe handling string recovered. The marine riser is re-installed but now connected to the top of the BOP stack.

4.3.3. *Subsea* BOP *stack*

The 200 t BOP system contains four or five vertically stacked ram BOPs with one or two annular BOPs; all effectively function as valves that close off the annular space around the drill string – or if necessary totally close off the hole when the drill string is withdrawn.

The stacks have a disconnect point above the uppermost ram BOP, which allows the annular BOP, and control system, to be recovered with the marine riser, temporarily leaving the major part of the BOP system on the seabed.

The jointing of the sections of BOP stack is resistant to bending loads in excess of 5.4 MN m while containing an internal pressure of 10000 lbf in^{-2} (69 MPa). Sealing rings are self-energizing to improve sealing ability as pressure and mechanical load increase: elastomeric sealing cannot be employed.

The high-pressure kill and choke line connections from the surface enter through valve-controlled access into the BOP stack between the rams. As the name suggests, they are employed as necessary for 'killing' or 'choking' back any pressure that could develop below a closed BOP.

BOP control systems. Remote surface control in deep water of some 60 BOP functions constitutes a system of critical importance. Normally the drilling fluid is classed as the primary control, but for deep water, with the possibility of an enforced disconnect or failure of a long marine riser, and instant loss of a significant part of the drilling fluid column hydrostatic pressure, the BOP and its control system may assume the role of primary control. The reaction time of the control system is also critical: a delay of more than 20 s could jeopardize the safety of the well. A closing function could require the transfer and control of some 80 litres of high-pressure operating fluid in some 15–20 s through relatively small bore tubes. Actuation at the BOP stack is by hydraulic power supplied from surface via lines, integral with the marine riser, which charge hydraulic accumulators on the stack; these minimize function operating time by eliminating pressure-drop delay through long supply lines.

Water depths beyond *ca.* 500 m impose an operative limit on the use of direct or servo-hydraulic remote control systems, and beyond 750 m on 'hard wire' individual conductor electro-hydraulic methods. Thus a system of multiplexed telemetry for executive commands and readback becomes mandatory. Hydraulic power is directed to the individual function by pilot control valves activated by the multiplexed signal; there is a complete identical back-up system.

Various adaptions of well established multiplexing technology with address, execute and indicate facilities allow the use of a simple small-diameter transmission line with minimum signal attenuation, crosstalk interference, and mechanical handling and storage requirements.

The hydraulic control valves and regulators are concentrated into two control units, which are retrieved with the marine riser. Various types of control are required, for example the annular BOP requires independent variable closing pressure control to allow the element to be only partly sealed on the drill stem so that the drill string can be slowly moved (to reposition the bit), although the closed element is holding back the well pressure. Overrides mechanically lock the ram preventers in the closed position – a requirement should the vessel move off location, taking the power source and control with it. An independent acoustic system allows limited emergency control of BOP and marine riser release functions should the transmission cables be severed.

Should the drilling bit be stuck on the bottom, and a well control or drive-off emergency dictate, a special set of rams are fitted with shearing knives and when closed sever the drill pipe and seal the well (cutting a drill pipe of 5 in (127 mm) outside diameter and $\frac{3}{8}$ in (10 mm) wall thickness with a yield strength of 135000 lbf in^{-2} (930 N mm^{-2}), within the confines of the BOP: no small engineering achievement).

The control system is located at the driller's position at the surface – with full functional data feedback – as a synoptic visual aid display. Additional control points are strategically positioned on the rig in case of untenability of the derrick floor area.

A hydraulic power supply and manifold and control system is positioned near the driller: some 100 kW of electrically driven pumps, supplemented with air-driven pumps supplied from an emergency air accumulator, provide hydraulic power at 3000–5000 lbf in^{-2} (20–35 MPa). Since the system employs a 'total loss' hydraulic concept, clean water with a suitable miscible lubricant–antifreeze–anti-bacterial–non-polluting additive is employed.

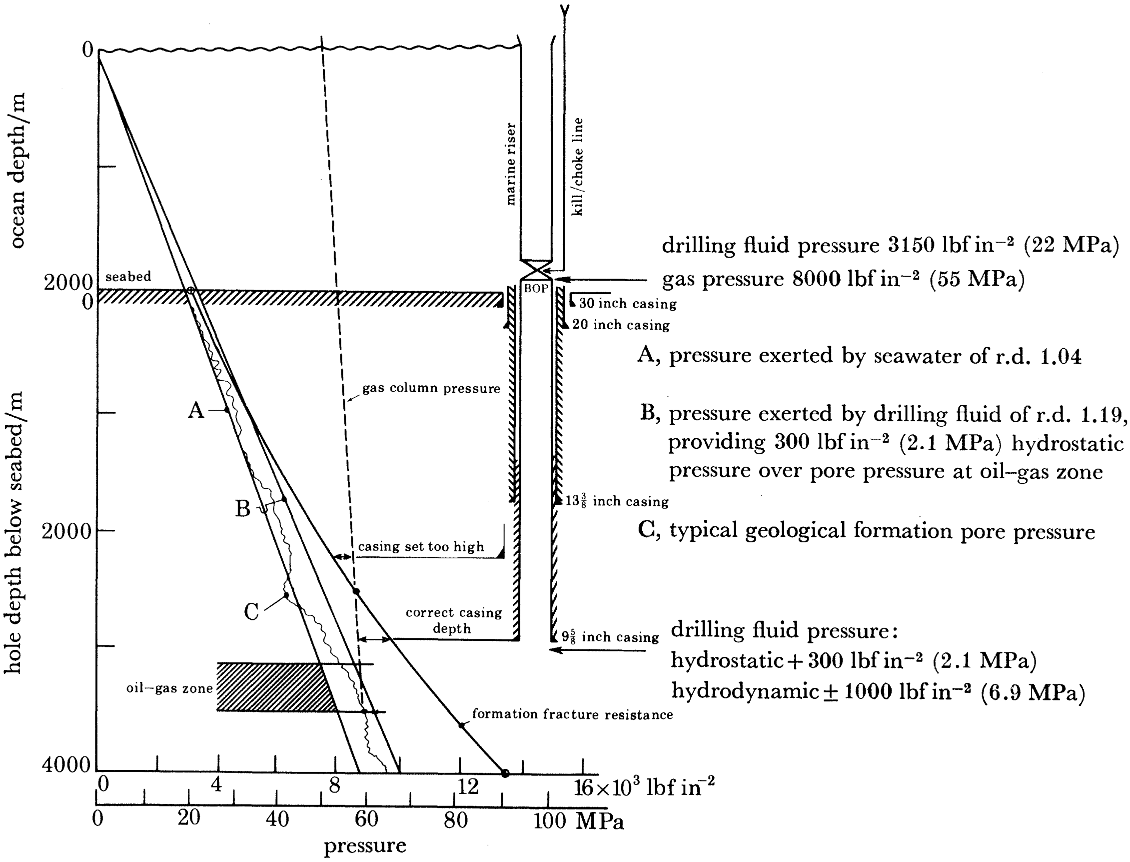

Figure 6. Typical pressure balance during deep-water drilling.

Control of well pressure. Conditions to consider on well control include:

the possibilities of a partial 'kick' escaping into the marine riser before surface indications dictate the closure of the BOP;

an ability to 'strip' the drilling string at great depth, under high bore hole pressure and high internal or external differential pressures through the annular BOP;

possible remote choking to control closed-in pressures at seabed level, since control applied from surface through 1000 m of 75 mm bore pipe would be impracticable.

4.3.4. *Handling the drill string*

The drill string is subject to a number of simultaneously applied varying stresses – onshore these consist of tension, torsion, hoop stress, and cyclic stresses from critical rotational speed instabilities and dynamic loads when drill pipe motion is arrested or accelerated. Superimposed on these, owing to the vessel's freedom of motion and off-hole displacement, are induced cyclic bending stresses at the water line and heave acceleration effects on the whole drill string, imparting nutational torque.

The use of drilling tubulars has to be carefully planned for these conditions, including correct material grades and diameter/thickness ratio to obtain the correct degree of flexibility, particularly near the ocean surface in the area of maximum angular motions. Under these conditions the drill string can be rapidly destroyed by the presence of hydrogen sulphides in the returning drilling fluid; an appropriate scavaging inhibitor may be introduced into the drilling fluid chemical recipe.

The drilling derrick is constructed for dynamic loading conditions and the simultaneous effect of wind gust on 4000 m of drill pipe racked in the derrick, under pitch and roll accelerations. To mitigate the effect of roll, sway, pitch and surge on the travelling hoist system, the moving section is held rigidly to the derrick by a dolly engaging a track. Accordingly, only the the highest winds and vessel motion adversely affect drill-string handling or drilling.

Cancelling out the effect of heave motion on the drill string. Although there is considerable inertial elasticity in a long drill string, it is necessary to cancel out heave motion, otherwise it would interfere with drilling progress as the weight on the bit would change, or, worse, the drill pipe could fail. Other operations would be adversely affected, for example landing long heavy casing strings, when a 250 t load is abruptly transferred from the vessel to the fixed support point at ocean-bed. When the BOP rams are closed on the pipe there is a short rigid link between the seabed and the rig, which requires motion to be cancelled.

The original method, still employed as specific conditions dictate, or as insurance, consists of a long-stroke bumper-sub (LSB). Originally employed for attempting to jar free a stuck drilling bit with $\frac{1}{2}$ m of vertical stroke, an extension to 2 m travel produced a useful motion-compensating device. Two or more would be positioned in the drill collars at the neutral tension point to satisfy the drilling weight criteria; by partly collapsing the LSB the driller can allow the bit to drill without the interference of heave motions.

The later method is to incorporate a motion compensator into either the derrick top or the travelling block system. By an oleopneumatic device the heave motion is cancelled out: the system can be passive or active with a stroke of between 6 and 15 m and a capacity of 300 t with a stroke/load ratio change of ± 5%. The setting is adjusted by the driller as required.

4.3.5. *Evaluation of well potential*

Drilling ahead in $12\frac{1}{4}$ in hole would then continue and $9\frac{5}{8}$ in casing would be installed, followed by $8\frac{1}{2}$ in hole and 7 in casing. In each event the casing is landed and sealed in the $16\frac{3}{4}$ in WHB, which also has provision to accept a tubing hanger should the well be completed as a producing well.

On completion of operations the well is plugged, the marine riser and BOP stack are recovered and the WBH and casings are either capped with a temporary corrosion cap or cut off below seabed level either by a cutter rotated by the drill string or by explosives. Consideration may have to be given to completion of potential production wells by incorporating specific ocean-bed equipment during the drilling phase for subsequent connection to production facilities.

Should it become necessary to evaluate the productive potential the following safe method is adopted.

(i) A test string (usually the drill pipe) complete with the relevant test valves to control any flow is run into the well and supported on a 'test tree' (incorporating dual fail-safe valves) in the BOP stack with the rams closed on it. From there it is connected to the surface by the drill string, and supported on the motion compensator.

(ii) By applying pressure to the annulus, an isolating packer is energized, sealing off the annulus space above the zone of interest; by additional annulus pressure, flow valves are opened; flow rates and associated pressures are recorded. Thus there are a number of independent safety controls built into the system, i.e. a reduction in annulus pressure would seal off the flow into the drill string, the valves in the test tree can be closed and the drill string to the surface disconnected by a special release mechanism. In effect the test exposes the zone to a reduced hydrostatic pressure, sometimes approaching atmospheric, to stimulate flow.

4.3.6. *Safety and emergency conditions*

At any stage during the drilling operation it may be necessary to suspend the drilling string in the WHB or on the BOP rams; rapid weather deterioration may leave only between 1 and 2 h to recover the drill string and disconnect the riser, normally a 3–6 h operation. To obviate this problem some drill pipe is recovered, calculated to place the bit into a safe position, a landing plug is inserted and the drill pipe is run back and supported either on the BOP rams or in the well head.

In an emergency the drill pipe can be landed on its tool joint on the BOP pipe rams, and sheared off with the BOP or mechanically backed off.

Operators employ a special operating and safety control procedural system employing colour codes to denote the degree of weather forecast hazards expected. These assist vessel management to plan accordingly and implement the necessary action, including preparation for emergencies. Specific operations cannot be started unless a corresponding clear forecast is available.

Considerable training and retraining is undertaken, including pre-operational familiarization.

New sophisticated navigational aids are employed in a constant drive to improve marine safety and performance.

5. ACHIEVING SUCCESS: LOGISTICS, PLANNING AND COSTS

The principal challenges to successful deep-water dynamically positioned drilling are:

station keeping;
remote geopressure control – the BOP system;
reducing the risk of formation fracture;
good maintenance;
appropriate human resources and personnel training;
equipment development and performance assessment;
creation of special purpose equipment;
application of basic drilling requirements and existing technology;
logistic planning; an essential consideration to ensure continuity of operations without having to wait on weather for delivery of equipment or a reduction in wave height to allow work boats to be unloaded;
adequate environmental, current profile, ocean-bed and sub-oceanbed data become vital before committing to a very expensive operation.

Costs are increasing at a disproportionate rate, apart from inflation, owing to the introduction of more advanced technology, the enforcement of different and stringent certification requirements by various countries, the incentive to improve safety and efficiency in ever deeper and more hazardous environments.

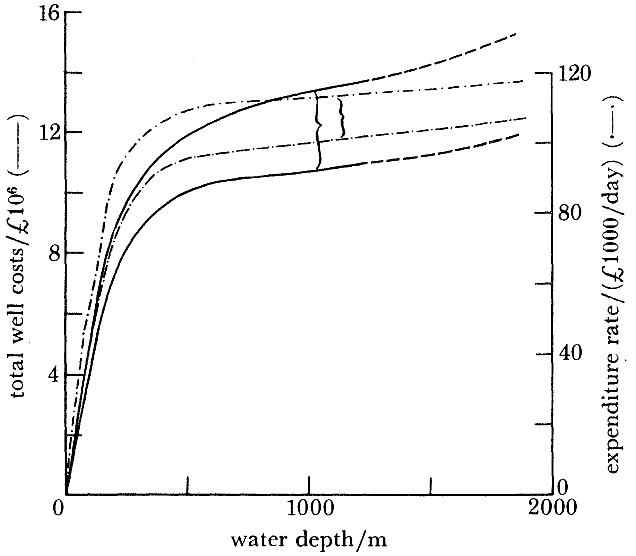

FIGURE 7. Relation between well costs and water depth for a 4000 m well. Braces indicate envelopes depending upon drillability, weather and degree of testing. The figures exclude mobilization and demobilization, and inflation. About 50% of the costs are for the hire of the drilling vessel. £1000/day ≈ 1.2 p/second.

6. THE FUTURE

There is a basic incentive to explore in ever deeper water as economic circumstances allow. The technological aspect is solvable, although large vessels and a more comprehensive marine riser system will be involved. The BOP system and control could be extended to 3000–4000 m water depths based upon present systems. The controlling influence is that of an economic strategic nature.

A contract has been awarded by the National Science Foundation for the design of a 4000 m (13000 ft) marine riser system for the Ocean Margin Drilling Program, possibly employing the *Glomar Explorer*.

Probably the connection of the flow line to a deep-water production system on the wellhead is the most difficult technical problem to solve. Production systems and their remote installation, control and maintenance, have already been designed for deep water and deployed in shallower waters for experience.

Tethered tension-leg production platforms, anchored semisubmersibles or dynamically positioned units could be employed as production units. Single well production concepts employed by an anchored ship are now under development. BP have pioneered SWOPS (Single Well Oil Production System). A British designed version of the tension-leg concept, the first, was effectively demonstrated off the Lancashire coast in the early 1960s.

The oil industry continuously depends upon advanced technology and technologists; the science and art are actively evolving.

APPENDIX. TERMS, ABBREVIATIONS AND UNITS

barge	common definition of a floating rig of any type
bit	the drilling bit, the tool that cuts the rock
blow-out	uncontrolled flowing of an oil or gas well
blow-out preventer (BOP)	well control valve at surface or seabed
casing	the steel tube lining the borehole
casing string	the whole casing of any size
drill collar	the heavy sections immediately above the bit
drill pipe	the section between drill collar and surface
drill string	the whole drilling assembly
drilling fluid	the special liquid circulated during drilling
drive-off	an uncontrolled movement away from the location by a DPDS
DPDS	dynamically positioned drill ship (one without any moorings or tether)
kick	the tendency of the well to flow due to geopressures
LSB	long-stroke bumper-sub (original form of motion compensator to cancel out heave effects)
Mohole	a project to drill to the Mohorovičić discontinuity (some 35000 ft (10.6 km))
marine riser	connects the seabed to the surface
PGB	permanent guide base
stripping	allowing movement of the drill string through a partly closed BOP
SSWH	subsea wellhead located on the ocean floor
TGB	temporary guide base
underground blow-out	uncontrolled fluid movement from a higher pressure to a lower pressure zone below ground level or ocean bed
VDL	variable deck load
WHB	wellhead body
HP	horse power (746 W)
lbf in^{-2}	‘p.s.i.’ (*ca.* 6900 Pa)
t	tonne (*ca.* 2205 lb)