PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Offshore Subsea Engineering [and Discussion]

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Offshore subsea engineering

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As a result of years of research and development work on subsea completions, manifolds and flowlines, followed by field installations in relatively shallow and calm waters, a number of well completion and flowline laying and connecting methods are available and operational. The installation methods are basically diverless and control and maintenance are achieved by sophisticated systems; likewise the floating offshore terminals such as the E.L.S.B.M. and the Spar have been designed, built and put into operation.

Although these systems were meant to be installed mainly in deeper waters, say beyond 210 m where diver access and the use of conventional techniques would become rather limited for technical and economic reasons, it is now evident that many fields in shallower waters can be more economically and efficiently developed or complemented by the use of deepwater techniques.

Current development work concentrates on the design and evaluation of multibore production risers, floating production platforms and pipelaying and repair.

My subject takes us to one of the furthest frontiers yet reached by modern oil technology. Before I discuss in a little detail the latest trends I should, I think, make the general point that although advances, stimulated particularly by the challenge of the North Sea, have been very rapid in recent years, the industry's capacity to produce oil and gas in deep water is still in its infancy.

As figure 1 shows, it is now possible to drill exploration wells from semi-submersible drilling rigs or drill-ships in more than 1000 m of water. This takes us right off the continental shelf upon which offshore operations have hitherto been concentrated and on to the steeply falling continental slope. A Shell company has drilled a well in 720 m of water off West Africa; Exxon have more recently gone deeper still – 1000 m offshore Thailand. These efforts, however, have so far not met any commercial success.

By contrast, for production drilling the present limit is about 200 m, the depth at which the Brent and Statfjord fields northeast of the Shetland Islands are being developed. There we still have to create an oasis of dry land above the sea as a base on which the work can be done. This oasis has been provided by huge platforms of steel and concrete upon which all the facilities for oil, gas and water production and separation can be established. These units are tremendously costly, particularly in the current climate of inflation. To take one example: since 1972 when the development of Brent began, the investment per daily barrel of peak producing capacity has doubled, to between \$6000 and \$9000 for the new generation of North Sea fields.

The four Brent production platforms and their facilities alone will together cost more than \$$10^9$. For Statfjord, in the Norwegian sector, the biggest North Sea field yet found, the cost of the initial platform will be more staggering still.

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It is well known that from each of these platforms it will be possible to drill some 40 deviated wells – that is to say wells which at depth will be widely spaced around the platform to tap the oil reservoir at a number of points. The wells are drilled vertically at first and then at an angle, to reach their required targets in the reservoir. The wells reaching out furthest will require a maximum angle of about 65 degrees and be 3 km from the platform. Even deviated wells are unable, however, to reach the whole of a very large reservoir, or isolated accumulations that are too small to justify individual platforms. So the basic problem is how to find means of completing and producing remote wells at costs that will meet our economic criteria.

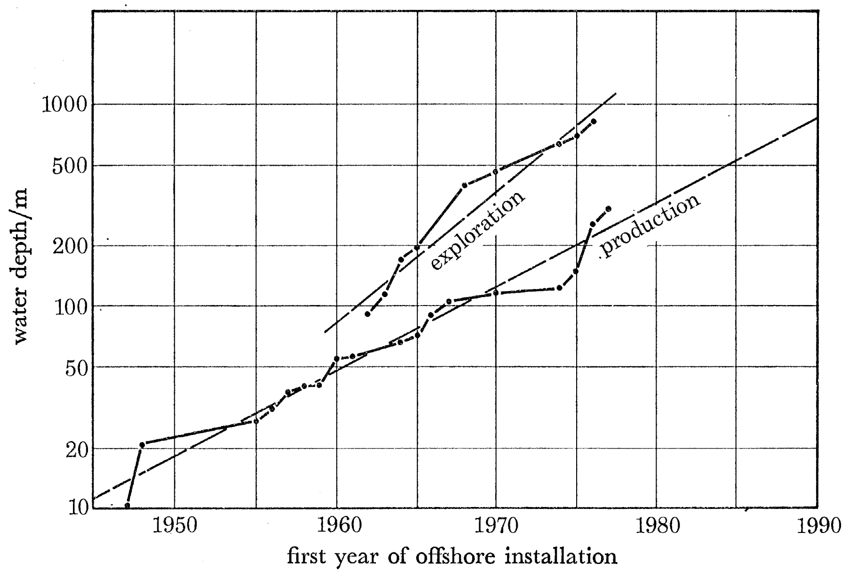

FIGURE 1. Maximum water depth for exploration and production.

Until comparatively recently it was generally believed that underwater well completions, floating production facilities and offshore loading and storage could only be justified in water too deep for fixed production platforms, the limit being 200–250 m. We have now, however, learned enough about the technology involved to appreciate that it can be applied not only to fields in deep water, but sometimes depending on the circumstances even more economically in shallower waters and with greater efficiency than conventional systems.

Figure 2, representing the development of a North Sea field, presents the problem diagrammatically. The production platform is shown in the centre of a circle and the black spots represent the wells to be drilled within it. You will see, however, that there are a number of wells which are well outside the reach of deviated drilling. These small and distant accumulations may, however, be susceptible to economic development by underwater completion techniques.

Two distinctly different problems are encountered here. The accumulation in the bottom left-hand corner calls for one producer at a distance of some 3.5 km from the platform. Production can be achieved by connecting the subsea completed well to the platform by means of an individual flowline.

The accumulation northeast of the platform is more complex and a total of four producers and three water-injection wells are presently foreseen. Moreover, the distance from the platform is approximately 6.5 km, which does not allow for individual flowlines because of excessive pressure losses in these lines. In this particular case use will have to be made of an underwater manifold which serves as collecting point for individual well streams.

Let us consider the two major building blocks that are required under the sea, e.g. the underwater well completion and the underwater manifold.

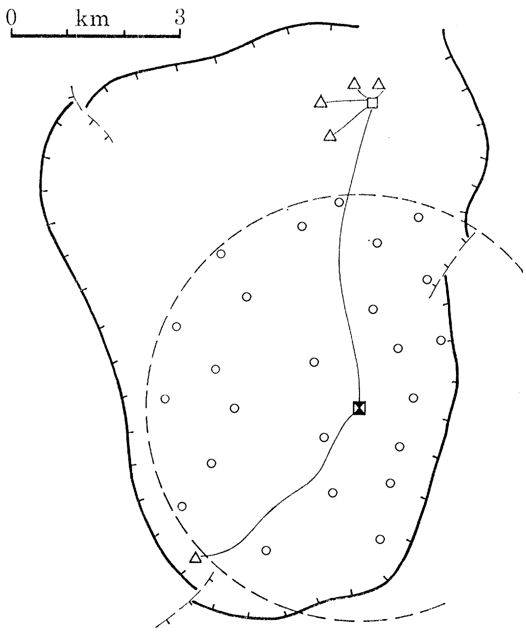

FIGURE 2. Use of satellite underwater completion wells and a subsea manifold in the North Sea. Quartered square, platform; ○, platform (deviated) producer; □, subsea manifold; △, underwater completion producer; ——, bottom laid flowline or bulkline.

One of the advantages of working in a major international community of companies is that a problem may be tackled in more than one way, the results compared, and a decision made which will serve the purpose best in a given set of circumstances. Research may also be shared with other groups working along different avenues towards the same goal. The size and spread of Shell companies' operations have enabled two separate approaches to be made to the problem of operating and maintaining subsea installations; by designing watertight air-filled compartments in which technicians can work in their shirt sleeves at the bottom of the sea; and alternatively by 'wet' subsea installations relying on remote control from the surface.

In 1972 research by Shell in the United States and Lockheed Petroleum Services led to the world's first ocean-floor well completion in a normal atmosphere wellhead chamber in 115 m of water in the Gulf of Mexico. Engineers sent down in a service capsule were able to assemble the wellhead equipment inside the steel chamber by using standard tools and techniques. Shell Oil has so far made nine underwater completions of which the earlier ones were of the 'wet' type.

On the other side of the world in Borneo, Brunei Shell Petroleum has completed ten underwater wells over the last nine years. A technique has been evolved by which subsurface work on the wells can be carried out by means of tools pumped down to the well through the crude oil flowline. Extensive tests on land have conclusively proved the feasibility of this method and many lessons have been learned on the reliability of submerged control systems (figure 3).

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While the wells in the Gulf of Mexico were equipped for rather low flow rates of about 500–1000 barrels per day, the Brunei wells were designed for flow rates of 5000–10000 barrels per day.

The technology acquired by separate but complementary research in two hemispheres is being coordinated and applied in deeper water and under more exacting physical conditions in the North Sea. Towards the end of last year Shell Expro made the first 'wet' well completion in the Brent field. Instead of a rigid steel flowline of the type hitherto used, a flexible high pressure steel flowline – rather like the hose of a vacuum cleaner – was devised to link the well with the platform. Although expensive to manufacture, flexible flowlines do not need pipelay barges and can be laid with low day-rate equipment.

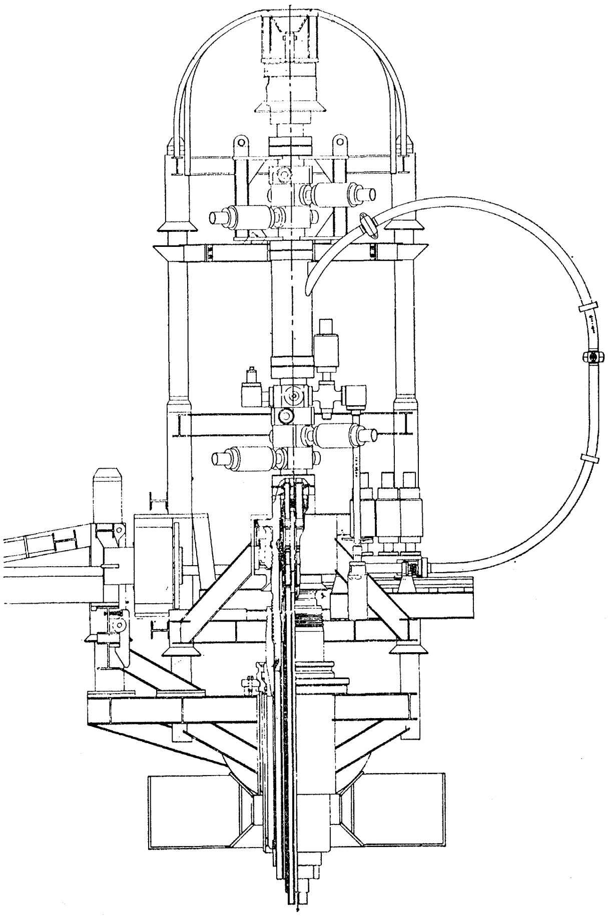

FIGURE 3. Brunei type underwater completion.

Let us now consider the second building block: the underwater manifold. Recently, field testing has begun in the Gulf of Mexico of a dry manifold centre which gathers, measures and controls production from three oil wells, two of which have been completed on the ocean floor.

Figure 4 gives an impression of an encapsulated well manifold centre. Its purpose is to serve as a collecting point – a sort of submarine flow station – to bring together the oil streams from a number of wells. The oil is then fed into a bulk line to the surface platform, thus avoiding a mass of costly flowlines and risers. Exxon has pioneered a wet manifold in the Gulf of Mexico at a depth of 54 m, and a French company has recently installed a prototype 'wet' manifold in shallow water offshore Gabon.

The next step is to design and build large manifold centres capable of handling the large daily flow rates expected from North Sea fields. The first of these (shown in figure 5) is being designed jointly by Shell Expro and the British Industry. The diagram gives no real impression of the size of the structure for which feasibility and engineering studies have been completed.

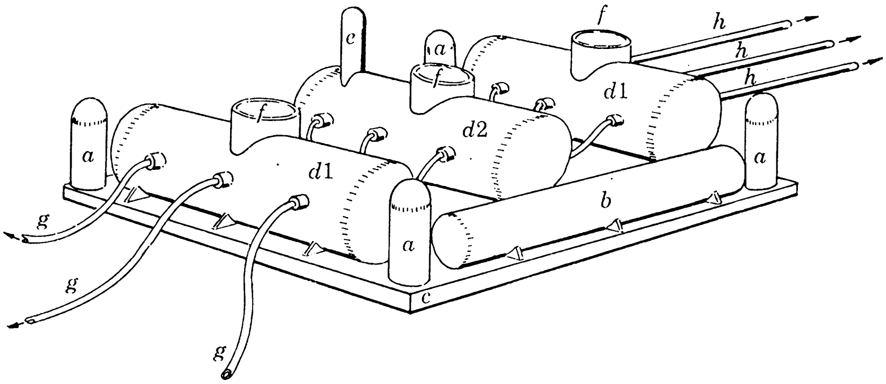

FIGURE 4. Shell Oil–Lockheed one-atmosphere dry manifold centre. The unit is floated to the site, sunk in position by flooding the ballast and trim chambers, and the flow, bulk, t.f.l. and control line bundles are pulled into the connection chambers, through sealing glands, by linear winches in chambers. (*a*) Trim tanks; (*b*) ballast tank; (*c*) raft foundation; (*d*) dry chambers; (*d*1) flowline, umbilical and bulkline connection chambers; (*d*2) manifold, instrumentation and test chamber; (*e*) test separator; (*f*) 'teacups' for mating of Lockheed transfer capsules; (*g*) flowline and control bundles to wells; (*h*) bulk, t.f.l. and control bundles to platform.

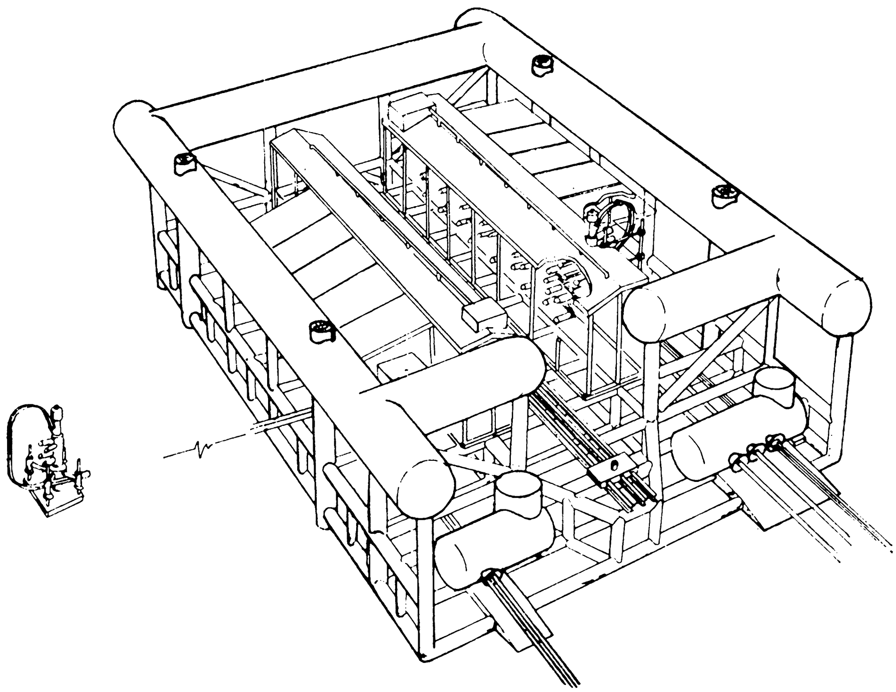

FIGURE 5. Shell Expro's proposed underwater manifold centre, accommodating both template drilled wells and tie-in points for satellite wells.

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It will be about 48 m long, 42 m wide and 12 m high and weigh 1800 t. The main framework or 'template' will incorporate bays for eight well locations with facilities for connecting satellite wells by flowline to the manifold.

Some elements of the 'dry chambers' pioneered by Shell Oil and Lockheed in the Gulf of Mexico might be incorporated, facilitating easier connection, maintenance and repairs, thus reducing the need for divers or other sophisticated connecting methods. Shell Expro are planning several underwater well manifolds in the North Sea in their programme.

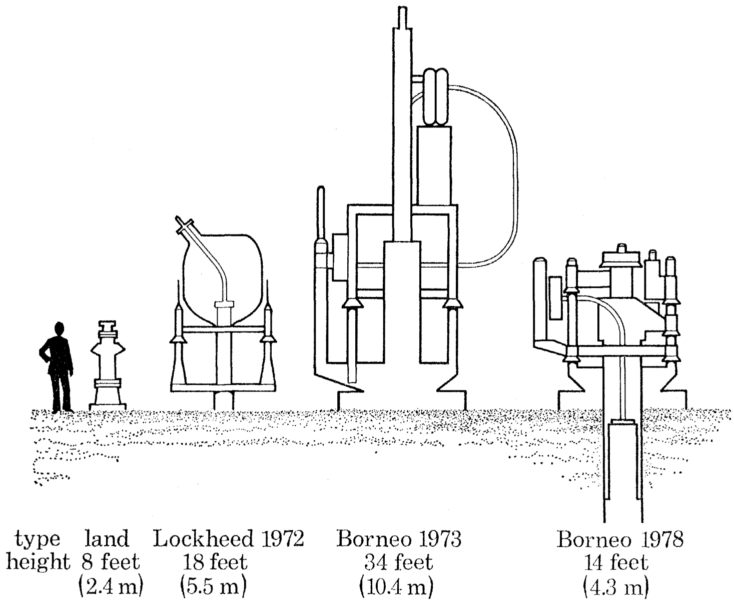

FIGURE 6. Subsea Christmas-tree profiles.

It is easy to appreciate that going under water calls for different technology and both wells and manifold are more expensive than conventional installations. One has only to glance at the sophisticated wellhead of the type used by Brunei Shell (see figure 6) to see how far we have moved from the comparatively simple Christmas tree of years gone by. It is appreciated that the height of the subsea wellhead could form a hazard if hit by trawler boards or dragging anchors. In an effort to minimize this risk, Shell International have designed a caisson type recessed tree concept which reduces the total height considerably and allows easier protection.

There is of course concern about the potential hazards of subsea installations from the point of view of operation, accessibility, inspection and maintenance. These aspects should be compared with the hazards of operation on conventional platforms. The factors affecting the safety of wells are, *inter alia*, size of clusters, probability of mechanical damage, fire risk and location of wells and process equipment.

On balance, we have concluded that the risks to which underwater installations are subjected to are on a par with the conventional facilities, if not less.

Of course, we have not yet reached the depth limit at which conventional fixed production platforms can work. In the United States, Shell Oil Company are building a steel platform for use in the Gulf of Mexico in more than 300 m of water (figure 7). The platform will be installed in three sections, one on top of the other, the first one of which will be placed this summer.

As can easily be appreciated, the depth capability of a floating structure is still much greater and the need for it might present itself soon. In April of this year Shell Teoranta began drilling an exploration well 220 km west of Ireland in 480 m of rough Atlantic water, using a Sedco-700 type semi-submersible. The well has now reached a depth of 3000 m.

I now turn to the various means by which oil can be produced from subsea wells and discuss the floating facilities required to process and handle it. What are the requirements to be met? First the well effluents must be taken up to the producing unit on the surface. Next each well might be tested individually to assess how much oil, gas and water is being produced. Then the treated crude, gas and water are conducted back via the bottom of the seafloor, either to an offloading point on the surface for oil or to an injecting point on the seabed (for gas or water).

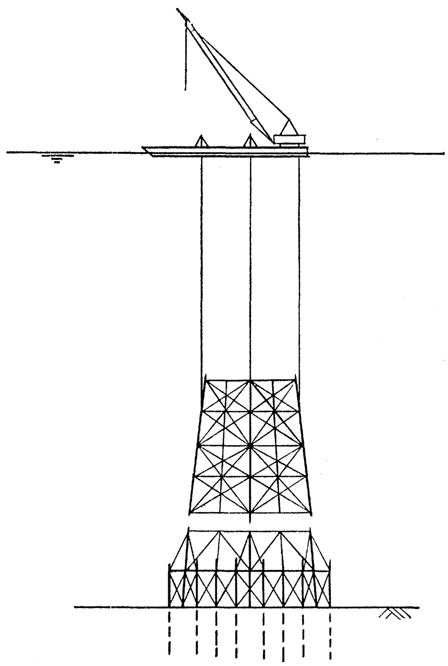

FIGURE 7. Multi-part platform (300 m water depth) for use in the Gulf of Mexico.

Hence a multi-functional number of conduits is needed, which is called the multibore production riser. Up and down and sideways movements of the surface facility with relation to the multibore riser have to be compensated for.

The first floating system installed in the North Sea was by Hamilton Brothers in the Argyll field, from which the first U.K. oil was shipped ashore in the summer of 1975.

A more recent development is the Single Anchor Leg Production System, S.A.L.S. (figure 8), for underwater wells. In this arrangement, a single anchor leg composed of chain links is connected from a universal joint at the bottom to a top swivel on the surface incorporating separate concentric flow paths for oil and for control hydraulics. A tanker is used as a floating base for production facilities and storage and the unit is able to swing on its axis in response to wind and wave forces. It is equipped with oil and gas separation equipment and facilities. The gas will be used as fuel in the ship's furnaces or burnt in specially built incinerators. Oil is loaded into a shuttle tanker which fills up alongside and takes it ashore. The first S.A.L.S. unit to be put to operational use was due to start work in June 1977 in an oilfield in 115 m of water east of Barcelona in Spain.

To overcome some of the limitations inherent in the single anchor leg system, we are studying a more complex layout which incorporates a bundle of conduits between the floater and the fixed manifold (illustrated in figure 9). Here there is a template manifold centre (*a*) on the seabed capable of accommodating six wells, with facilities for connecting satellite wells (*b*) through flowlines. The oil comes up through the production riser (*c*), which incorporates a number of flowlines and one 'export line'. The semi-submersible platform on the surface (*d*) has the necessary production facilities. After processing, the oil is pumped back through the manifold for loading into the tanker via the export line (*e*) and the single anchor leg (*f*) into the storage vessel, to which a shuttle tanker (*g*) can be moored. This system is suitable for use in deeper water.

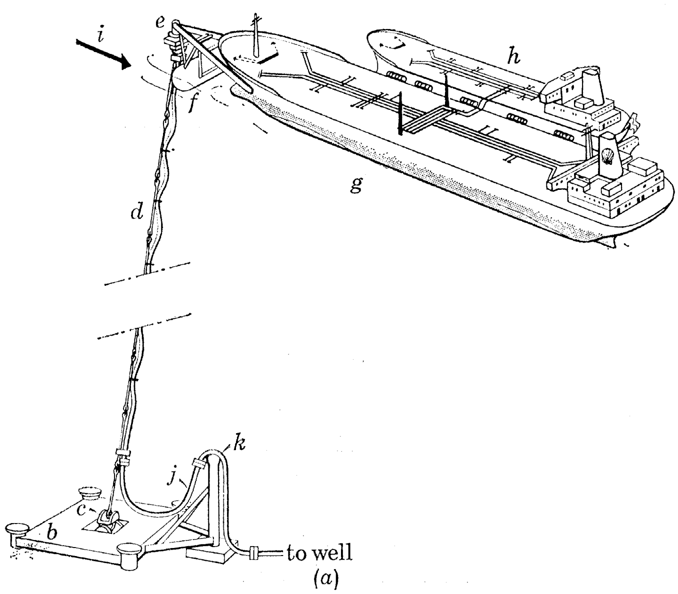

FIGURE 8. 'S.A.L.S.' installation for single field. (*a*) Underwater completed well with wet Christmas tree; (*b*) four-pile base; (*c*) bottom universal joint; (*d*) Single Anchor Leg composed of 'bicycle' type chain links, each approx. 16 ft long and 8 in in diameter; (*e*) top swivel with separate concentric flow paths for oil and for control hydraulics; (*f*) mooring 'A' frame with cylindrical flotation tank to maintain anchor leg in tension; (*g*) floating unit storage (f.u.s.) tanker with oil/gas separation facilities; gas is burned in ship's furnaces and in a closed incinerator; flaring is not permitted; (*h*) shuttle tanker carries oil to shore; shuttle may now moor alongside in calm environments but will moor in line from bows in rougher weather areas; (*i*) f.u.s. tanker is free to 'weathervane' but can be moored by her own bow anchors over the well to allow wireline maintenance of the well; (*j*) 'Coflexip' flexible flowline carries the well stream to the surface via swivel (*e*) and jumpers over 'A' frame; (*k*) conventional steel flowline.

It will be appreciated that we are moving by gradual evolutionary steps to improve our grasp of subsea engineering technology. The manifold centre development is a great advance towards eliminating a clutter of steel spaghetti on the seabed, apart from the operational advantages it brings. One of the more interesting techniques is the one known as 't.f.l.' (through the flowline) maintenance of wells. In the system I have just described it will be feasible to reach the wells from the platform without the help of divers by passing tools through the flow-line using a hydraulic circuit. The tools are mounted on what I might call a 'hydraulic loco-motive' and by selecting the proper tool subsurface valves in the well-bore can be operated or

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exchanged. Operations can be monitored from the surface. Unlike the conventional method of running tools down on a wire line vertically, for which a semi-submersible is required, the hydraulic system will be able both to 'push' and 'pull' the tools and to enter the well from a remote point.

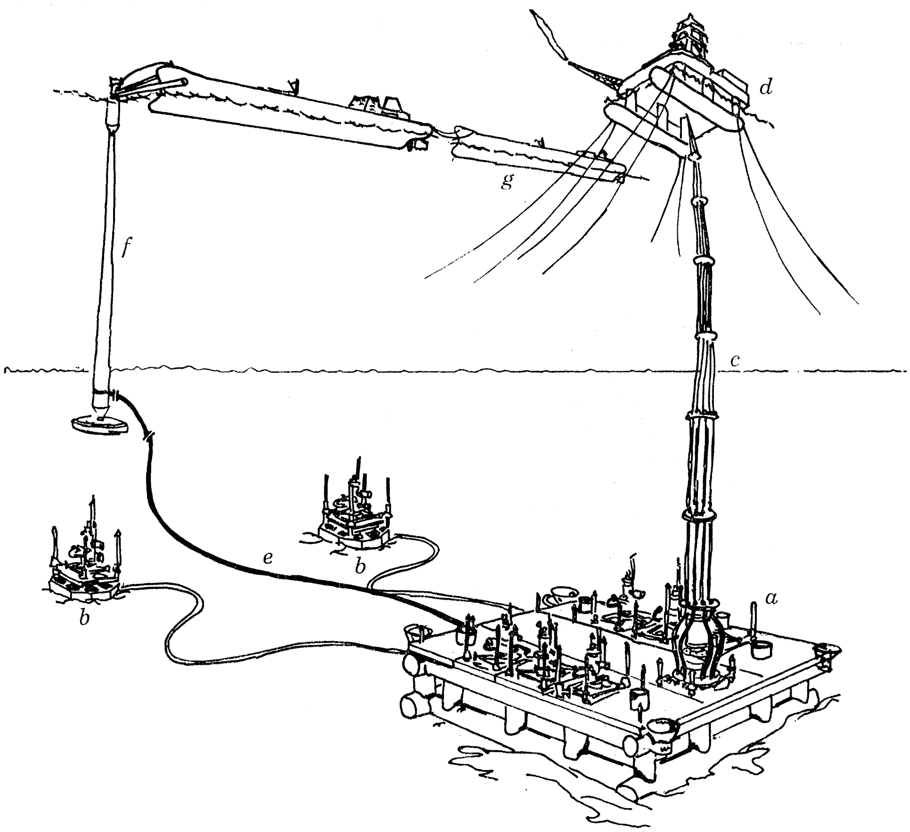

FIGURE 9. Floating production facility with subsea completions. (*a*) Six-well completion template; (*b*) satellite wells tied to template by flowline; (*c*) production riser: eight flowlines and one export line; (*d*) semi-submersible with production facilities; (*e*) export line; (*f*) S.A.L.M. with A-frame-moored f.u.s. tanker; (*g*) shuttle tanker, stern moored to f.u.s. tanker. Well maintenance is by wireline.

Figure 10 shows a still more advanced means of producing oil from subsea wells by a floating platform anchored vertically by tension lines which hold it in place. The platform is moored securely to the bottom base-plate with the multi-riser system enclosed within it. Vertical motions are supressed due to the constant distance between the platforms and the anchoring point.

I should now like to mention surface storage systems. The Shell-designed storage and loading facility known as Spar consists of a floating cylinder rather like an enclosed inverted wine glass some 100 m high, and with a diameter of 30 m, able to hold 3×10^5 barrels of oil. Pending the completion of a pipeline system to shore, the Brent field is being initially produced through a Spar installation. Tankers are loaded through flexible hoses, with the oil fed into the Spar from a pipeline manifold on the seabed connected to the producing platforms. We are now studying the possibility of developing a semi-Spar production, storage and offloading system, linked with a manifold centre on the seabed. The concept is illustrated in figure 11.

The systems which I have described are to a certain extent dependent on sea-bottom pipelines. We are now laying large diameter pipelines in 150 m of water and recently a 16-in pipeline was laid in 550 m of water in the Straits of Sicily as a test. Furthermore a joint-industry effort (with 37 participants) is well on its way to develop methods for laying 30-in pipelines in 1000 m of water. Attention is also given to repair methods and a feasibility study has just been concluded for a remote controlled subsea repair vehicle.

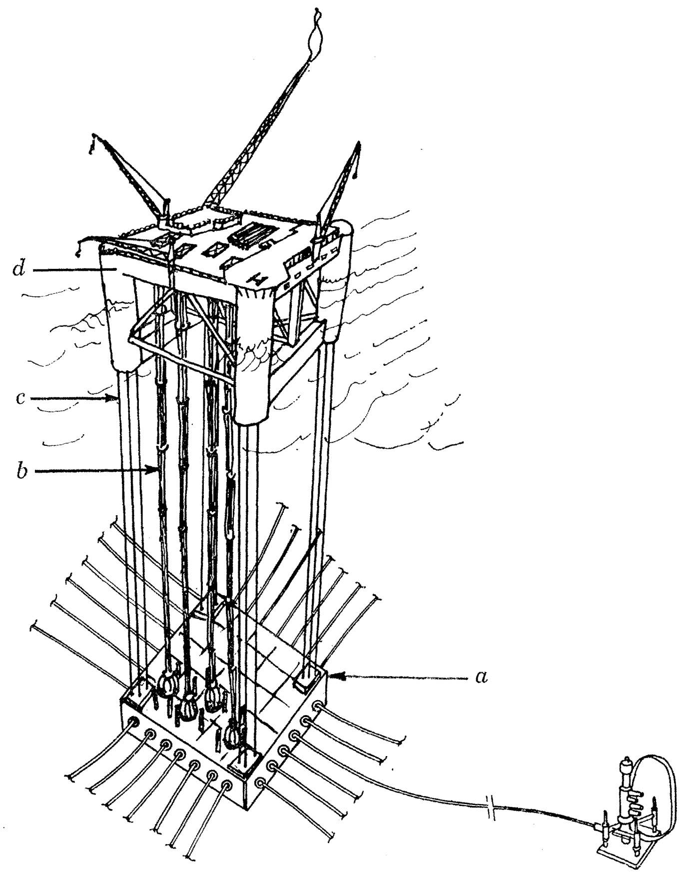

FIGURE 10. T.P.P. production system. (*a*) Bottom baseplate; (*b*) riser system; (*c*) mooring system; (*d*) T.P.P. unit.

As pipeline laying methods gradually develop into underwater construction, hyperbaric welding techniques will be improved upon. Experiments with this technique have proved the feasibility in 300 m of water and this method is now routinely used to make pipeline tie-ins in the North Sea in 150 m of water. Hyperbaric welding techniques are of course necessary if bottom-tow construction methods are to be developed to full maturity.

In carrying out all these exacting tasks in extreme physical conditions, one can hardly overestimate the importance of precise weather monitoring equipment, which is vital in assessing design criteria and the safety and reliability of the equipment. In the exploration phase the annual fair weather season could be selected for drilling operations; in the production phase the weather must be coped with all the year round. Hence weather buoys have been developed which collect data (including profiles of currents from the surface to the sea bottom), and transmit information at regular intervals.

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The combined efforts of Shell International and Marine Exploration Limited (Marex) have resulted in the design of an oceanographic data gathering buoy (figure 12) for remote and exposed areas. A prototype was tested in 1975 in the Celtic Sea and a self-recording version was launched in the Atlantic north of Scotland last December. It has functioned well even in the extremely bad weather of last winter, and is providing data about an area of which limited detailed environmental information is available.

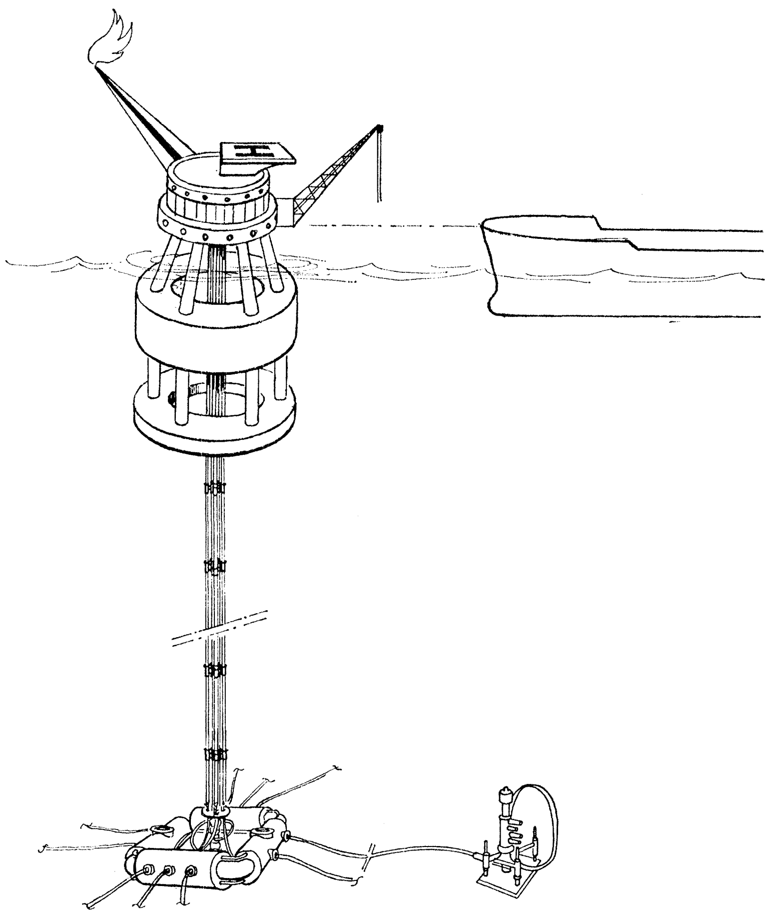

FIGURE 11. Semi-Spar production (storage) offloading system.

I have briefly mentioned the individual components under study. What we are now working towards is the conceptual design of complete production systems, incorporating subsea completed wells, manifolds, risers and floating units. There are relatively small oil accumulations where the provision of additional production platforms at enormous cost could not be justified, but where a combination of subsea wells and manifold with a floating facility on the surface might, be economic.

The offshore storage and loading terminal has also proved its practicality, although problems do still occur.

I hope that it will not be felt that I have been leading a guided tour through a Technological Wonderland under the Sea or indulging in a Jules Verne fantasy. There is nothing visionary or speculative about the technology which now exists. It *does* work. There are now nearly 30 producing Shell wells on the seabed in various parts of the world.

Taking into account the steep rise in the price of all forms of energy, and hence oil's ability to bear higher technical costs than in the past, there are grounds for confidence that subsea engineering can provide technological solutions to development problems which can be economically applied. I am convinced that floating systems will play an important rôle in deep water in the future and provide a competitive alternative to conventional platform development in shallow water.

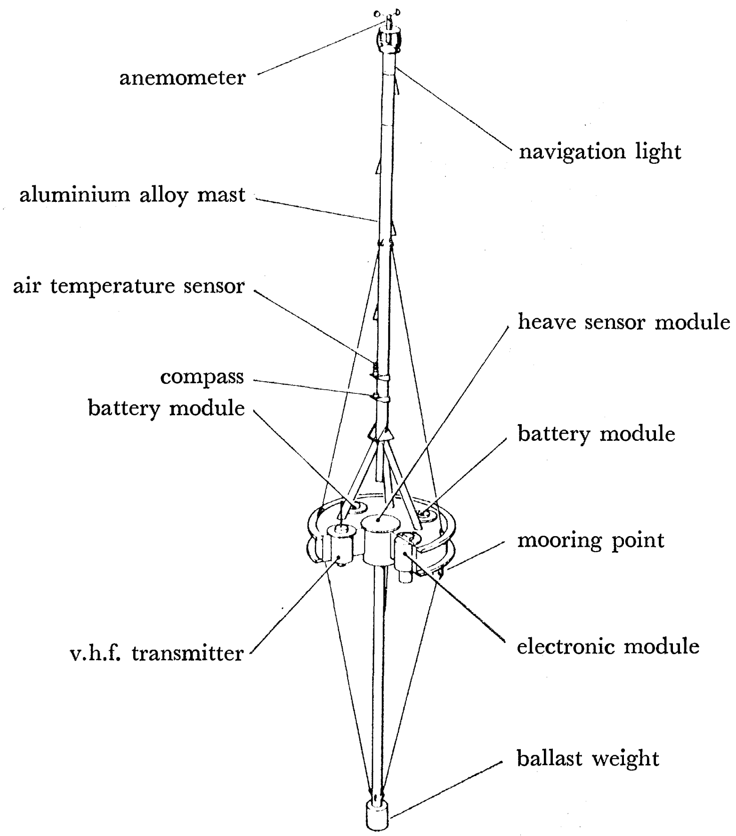

FIGURE 12. Data buoy: overall length 16.6 m; total weight 1000 kg.

Discussion

T. S. McROBERTS (*Q.M.C. Anchor Technology Ltd.*, 229 *Mile End Road*, *London E*1 4*AA*). Mr Goldman has given us a broad sweep of subsea technology and its problems. It raises a number of questions but I shall confine myself to one in which I have a personal interest. The anchoring problems are likely to be very considerable as we move into deep waters and more and more of these structures have to be floated, perhaps in groups. Could he tell us a little about any special problems he can foresee in deep waters?

E. C. GOLDMAN. Anchoring problems have already been encountered in shallower water, e.g. dragging of conventional type anchors, use of 'piggy-back' anchors or drilled-in anchor piles to cope with adverse soil conditions, wear and fatigue of chain and wire rope. Moving into deeper water will aggravate these problems.

In particular the seabed mooring points are a point of concern. The tendency of using wire rope with reduced lengths to minimize the weight to be carried by the floater will cause a vertical component of the anchoring force to act on the anchors particularly during major storms. Such considerations necessitate additional corrective measures.

Conventional types of anchors are not suitable and therefore supplementary means should be developed. In this connection assistance from propulsion units to safely ride out major storms could be a good engineering solution. Such a solution gives the possibility of reducing the offset of the floater which is likely to be required because of the weak restoring force characteristic inherent in deep water anchoring systems.

J. Black (63 *The Woodlands*, *Esher*, *Surrey*, *U.K.*). What is the maximum sea-state which allows a tanker to moor at a Spar buoy? Please describe the method used by shipboard personnel to pick up the floating mooring hawser in such a sea condition, bearing in mind the importance of tanker turn-round time and the need to prevent damage to the Spar mooring.

E. C. Goldman. The present, although still early, experience in mooring-up of tankers to Spar is that the procedure is still safely performed in seas of approximately 12 ft significant wave height and wind speeds of up to 25 knots.

The applied and well-proven method is basically that the shipboard personnel uses a grapnel, or in some cases an airgun, to recover a nylon messenger line of 3 in diameter and 1000 ft long, which is streamed out from the Spar upon arrival of the tanker. The messenger line is put subsequently on the ship's winch, and kept reasonably taut by heaving it in while the tanker is slowly approaching Spar. Both the main mooring hawser and loading hose connection wire are attached to the end of the messenger line. When the chafing chain of the hawser has come on board and been secured on the stopper, the hoses are pulled across and connected to the ship's manifold and loading can commence.

During the mooring the ship gives 5–10 t astern propulsion depending on the sea condition. Quick-release devices are incorporated to protect the mooring and hose connections. The total procedure in extreme conditions has taken a maximum of $1\frac{1}{2}$ h.

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