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The development of diverless subsea production systems

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SYNOPSIS

The potential need to produce hydrocarbons from deep water offshore fields has created a fundamental requirement to develop highly reliable subsea equipment which can be simply and effectively maintained without the aid of divers.

Reliability can essentially be achieved by utilising simple, field proven equipment, wherever practicable, and by only accepting direct extensions of current technology when suitable equipment is not available. The maintainability of subsea systems is the most dominant factor affecting virtually every aspect of deep water equipment design; it can also have a major impact on other aspects of field operations, especially the type of surface facility from which to deploy maintenance intervention equipment.

Many approaches to diverless maintenance of subsea production facilities have been considered in recent years. Those addressed in the paper range from one-atmosphere systems to state-of-the-art deep water systems currently under development for potential application in the hostile waters of the northern North Sea and west of Shetlands.

Irrespective of which of the several available approaches to diverless intervention is selected, the design of subsea systems will involve the trade-off of different arrangements, systems and equipment in order to arrive at an optimum, cost-effective design. In some notable recent projects this has been achieved by computer simulation techniques which evaluate failure rates, repair procedures and constraints, time to repair, and the environmental conditions under which maintenance operation can be performed. The paper concludes with an example of such an approach to subsea production systems design.

INTRODUCTION

Field developments in water depths down to 750 m have been under consideration in recent years and it is the technology being evolved for such applications that will strongly influence all future offshore developments, embracing those in shallow water, deep water and those located in Arctic and other frontier regions of the world.

The evolution of subsea production systems now renders production in deep and hostile waters technically feasible, although dependence upon sea bed completed wells will require the development of highly reliable and readily maintainable equipment and systems, capable of operating at water depths at which saturation diving is currently not, and may never become, a routine operation. Such requirements have necessitated that major emphasis be given to the application of a systematic, integrated systems engineering approach to the design of subsea production facilities.

Major design and operational challenges are imposed upon the design of subsea production systems for hostile, deep water environments; addressing these challenges has probably created the most rapidly developing area in the field of offshore technology.

This paper outlines the evolution of subsea production technology, the design approaches necessary to produce reliable and highly maintainable subsea systems and describes several major state-of-the-art subsea multi-well template/manifold systems. An example of the application of computer simulation techniques to optimise subsea production and topside support facilities design, is also presented.

Stewart M Adamson has over 30 years practical, technical and managerial experience in marine engineering and the offshore oil industry. His experience includes a 5 year engineering apprenticeship on Tyneside with Hawthorn Leslie (Engineers) Ltd during which time he attended Durham University graduating with honours in Marine Engineering in 1964 and was awarded the University's Stephenson Medal for technical excellence. He subsequently became Research Engineer with BSRA and joined Vosper Thorneycroft as Chief Engineer Designer in 1968. Since 1974 Stewart has been involved in the design and application of subsea production systems as European Manager of Lockhead Petroleum Services and Managing Director of Kongsberg Engineering. He is currently Managing Director of Fuel Subsea Engineering Ltd.

DESIGN ASPECTS OF DEEP WATER SUBSEA PRODUCTION SYSTEMS

The range of equipment design and operational philosophies which need to be thoroughly evaluated in developing an effective subsea production facility include the following.

1. Subsea well completion/manifolding: equipment could be incorporated within 1 atm encapsulation chambers or exposed directly to sea bed ambient wet conditions.
2. Installation and maintenance: diverless intervention techniques will be required; in very deep water guidelineless intervention may be necessary.

3. Well grouping options: vertically drilled, single satellite wells, clustered wells, or template drilled wells, the latter two being deviated wells.
4. Well servicing philosophy: wireline servicing from a surface vessel, subsea wirelining, or by TFL (through flow line) techniques from a field processing facility.
5. Flowline arrangements: utilisation of individual flowlines from each subsea well or commingling well streams from groups of wells into manifolds; bundled flowlines must also be considered for both individual and commingled flowline options.
6. Well control and monitoring: consideration of various combinations of electrical and hydraulic options; simple hydraulic control, versatile multiplexed electrohydraulic systems, or by state-of-the-art acoustic systems.
7. Protection of subsea equipment: trade-off between the need to protect against dragged anchors, fishing equipment and dropped objects, and the provision of unimpeded access to facilitate maintenance intervention operations. Embodiment of hydrocarbon leakage detection arrangements should also be considered.

The development of reliable and readily maintainable subsea production systems is engineering-intensive and the above areas constitute fundamental interactive groupings of key subsea production elements. Although methods selected in any particular area can have a significant impact upon others (see Fig 1), reliability and maintenance intervention aspects will have the greatest overall impact.

Reliability and maintainability

The design of subsea equipment for operation in offshore fields is dominated by the need to achieve high reliability coupled with ensuring that subsea maintenance intervention activities can he readily and efficiently accomplished.

Maximum equipment reliability can best be attained by strict adherence to a philosophy of simplicity of design, maximum practicable utilisation of field-proven equipment and minimising known potential failure sources, such as seals and active components.

Maintenance intervention operations are of vital importance since, by their very nature, they are essential for ensuring that, should a failure occur, field production downtime is minimised, and thereby rate of return on capital invested in a field development is maximised. Inspection and corrective maintenance operations on subsea installations are difficult and costly, especially in deep water. The requirement for intervention should therefore be reduced to a minimum by: using equipment which is simple in design and of rugged construction; limiting equipment installed on the sea bed to items essential for the safe operation of the system by ensuring that all subsea equipment is subjected to stringent quality assurance procedures throughout all phases of design, manufacture, installation and operation; conducting a suitable land testing program.

The ability to maintain (or restore) any particular subsea component or equipment at a predetermined operational state is dependent upon:

1. effectiveness of selected intervention systems in the performance of subsea maintenance activities;
2. design and layout of subsea equipment;
3. the time taken to effect planned maintenance and repair;
4. cost of maintaining (or restoring) fully operational status of subsea equipment.

In addressing these key issues, an integrated systems engineering approach is required in which paramount emphasis is given to:

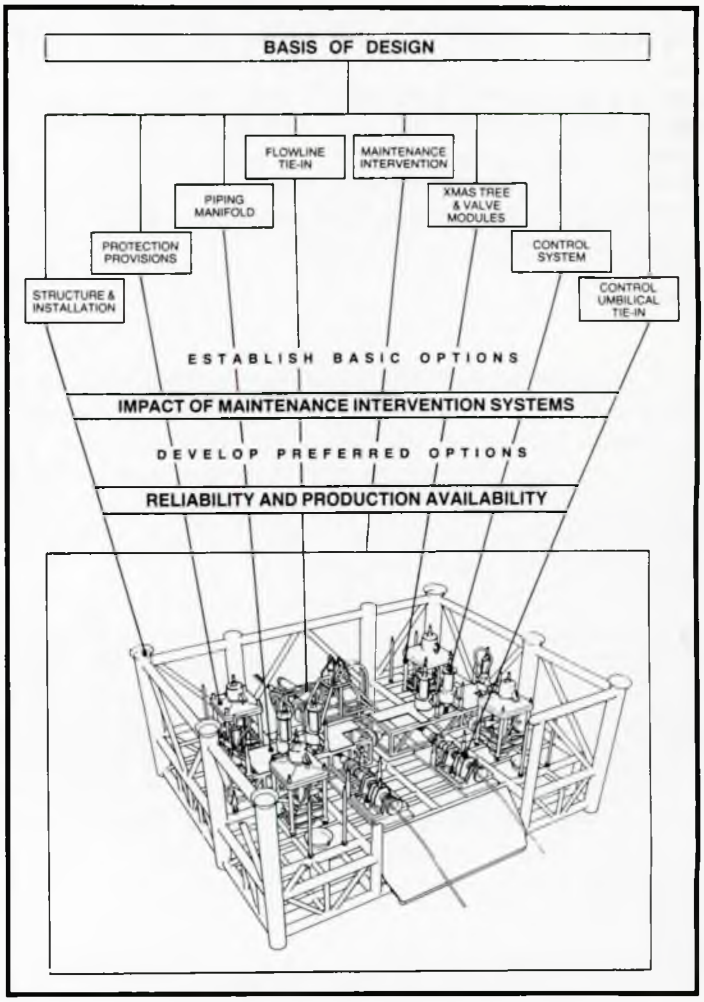


Fig 1: Template design methodology

1. the need to fully establish all 'topside' facilities necessary to provide maintenance support for subsea installed facilities;
2. embodiment of simple and effective means within a subsea production system design to identify failed equipment and to facilitate replacement;
3. provision of unimpeded access for surface retrieval of equipment or, in some cases, the execution of *in situ* repair of subsea equipment.

Particular emphasis must be placed upon utilisation of proven equipment in achieving these objectives unless it can be demonstrated that the application of innovative equipment can radically improve reliability and cost. In practice, a balance between utilisation of proprietary subsea equipment designs and new technology will be necessary.

Maintenance intervention activities

Maintenance intervention operations on subsea Xmas trees and other production equipment have evolved from the early applications in which every operation was conducted either entirely by or with substantial assistance from divers, to current developments which necessitate installation and maintenance predominantly by diverless and possibly guidelineless means (see Fig 2).

Intervention activities are of overriding importance in the development of functional and efficient deep water subsea production systems. In the case of a multi-well template/

manifold system, they will typically range from general observation tasks to major well workover and will require the application of a range of intervention vehicles and associated tools. Many such activities could be conducted as part of planned maintenance routines but some will be necessitated by random malfunctioning of equipment.

Selection of an effective maintenance intervention philosophy interacts with every facet of subsea production system design. This philosophy will be influenced not only by the range of subsea equipment utilised and the installed location, but also by the manner in which it is maintained. A subsea system in which components are installed and retrieved individually, will necessitate a different approach to maintenance intervention than a system in which key components are packaged in 'modules' which would be retrieved to the surface for repair; some fundamental operational similarities will however exist in intervention requirements of the alternative design approaches.

The range of available maintenance intervention systems which could be considered is presented in Fig 3.

Equipment requiring subsea maintenance

Equipment within a subsea multi-well template/manifold system for which maintenance intervention operations must be established would typically include:

1. Xmas tree and associated equipment;
2. production equipment and/or modules;
3. piping system/module;
4. connectors;
5. control pod;
6. flowline connection arrangements;
7. control umbilical connection arrangements;
8. main template structure;
9. damage protection provisions.

Maintenance intervention operations can be conveniently classified as:

1. observation
2. manipulation
3. installation and retrieval.

These operations will range from simple observation for inspection purposes to the major task of equipment removal, a range which will necessitate the application of different types of intervention tools and support vehicles. During the initial conceptual design stage of a subsea multi-well template/manifold system, maintenance intervention tasks should be grouped within these three classifications and intervention requirements and any preferred methods of execution established. Available intervention systems should then be reviewed against the specified intervention tasks in order to identify a preferred system. Criteria against which intervention system selection would be evaluated include:

1. ability to execute tasks efficiently;
2. system manoeuvrability;
3. topside support requirements and deployment techniques;
4. weather dependency;
5. potential risk of damage to adjacent equipment;
6. safety to human life;
7. operator preferences.

An outline methodology for the establishment of a suitable maintenance intervention philosophy, embracing the foregoing considerations, is summarised in Fig 4.

Diverless subsea production systems

Some diverless systems have been installed and operated (or tested) in recent years in water depths down to approx 400 m [eg Marimba, Garoupa, Central Cormorant Underwater Manifold Centre (UMC), Skuld], but in every case diver

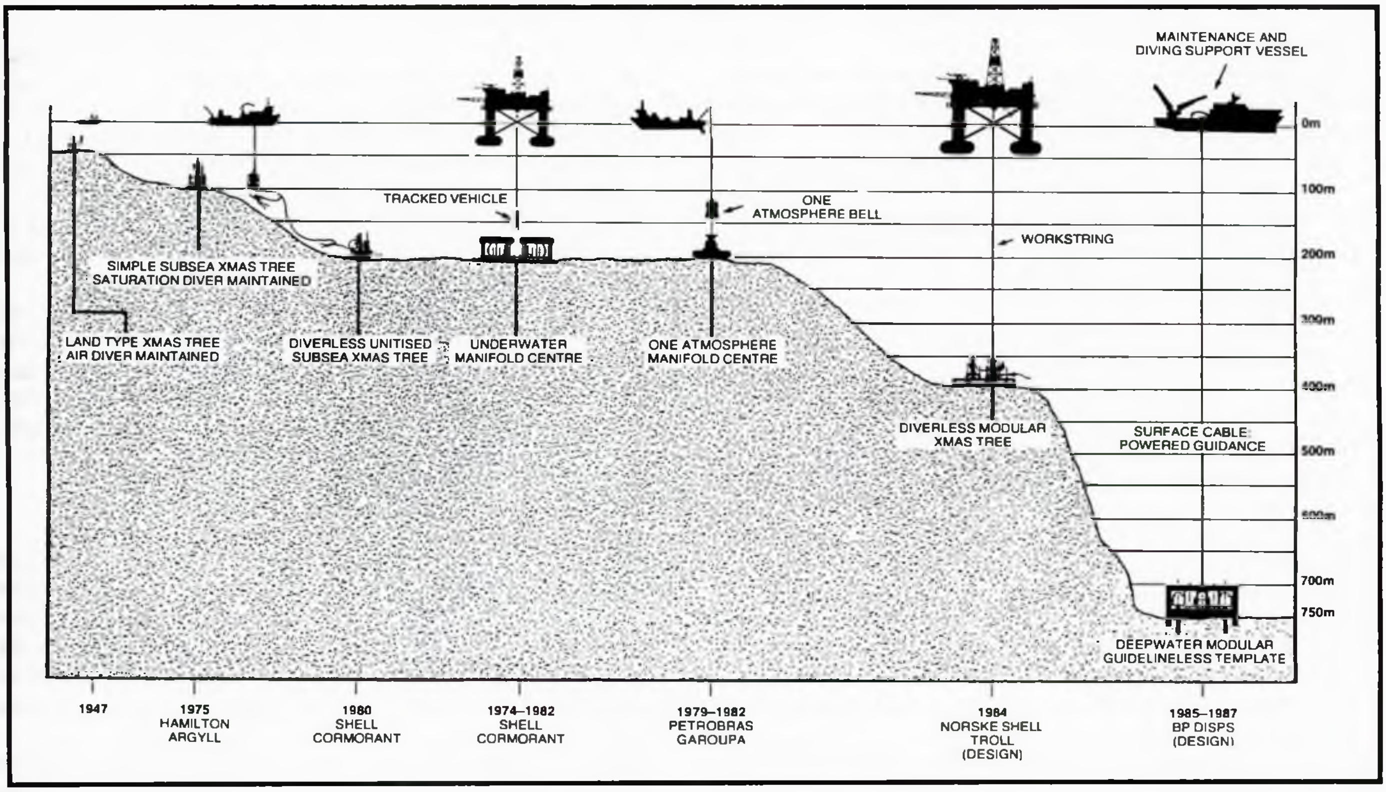


Fig 2: Evolution of subsea production systems

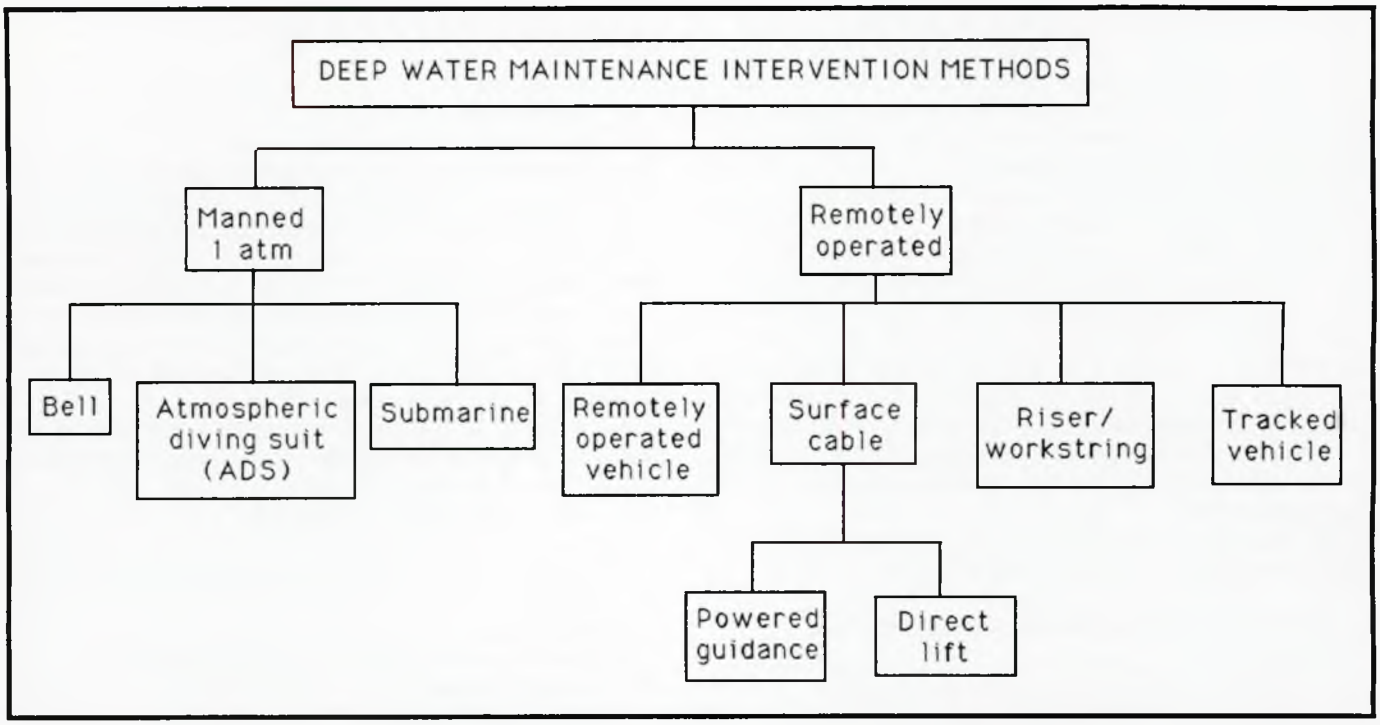


Fig 3: Range of deep water intervention systems

intervention has been resorted to, either because diverless methods have failed or in order to more quickly reinstate production from the subsea installation.

In addition, several commercial and engineering development programs for multi-well template/manifold systems are underway, in which diverless intervention methods different from those employed on the UMC, Garoupa, East Frigg (Skuld) and Troll are utilised. These programs are being pursued by BP (DISPS), Esso (EDIPS) and Mobil (SAS).

Although differing in the method of effecting diverless intervention all of the diverless systems mentioned above conform to one of the following philosophies for the maintenance of subsea equipment.

1. Surface retrieval: equipment exposed to sea water (ie wet system), with components and/or packages of equipment retrieved to surface for repair/replacement.
2. *In situ* maintenance: equipment exposed to the sea water and maintained on the sea bed *in situ.*
3. Encapsulation: equipment is encapsulated within 1 atm enclosures (normally breathable air) to facilitate access by trained oil field technicians.

Surface retrieval

Surface retrieval is tending to become the most commonly adopted approach to subsea maintenance and BP DISPS, East Frigg (Skuld) and Troll are all designed on this basis. In this approach individual components or modules are disconnected and recovered to the surface using workstring, remotely operated vehicles (ROVs) subject to capacity limitation, or surface cable systems, sometimes working in conjunction with an ROV.

A modular system involves the packaging of equipment into retrievable units, the boundaries/interfaces of which are primarily governed by functional requirements and reliability of individual components, coupled with overall size and weight of modules. Components most prone to failure, and thereby necessitating more frequent replacement, tend to be those which are most regularly operated, are complex in design and are operationally unproven.

It is therefore beneficial to group such components together and to facilitate their replacement with minimum disruption to other template-installed equipment. A further advantage of the retrievable modular approach is that only the template (not the entire subsea production system) needs to be positioned on the sea bed at the time of well drilling; in systems designed on an individual component basis much of the equipment would be fitted on the template at the time of installation.

Modular template designs currently fall into two basic alternative categories; viz those in which intermodule connection arrangements are accomplished by ‘conventional’ vertical connectors, and those based upon the application of horizontal connectors.

Utilisation of horizontal connectors results in a more accessible template arrangement with totally independent module removal and replacement and enables connector seals to be more readily inserted and retrieved. These considerations must be balanced against the fact that horizontal connector stroke requirements necessitate that a significant degree of piping flexibility be built into the module or into the template pipework. Such connectors are also comparatively unproven, whereas vertical connectors have been and continue to be utilised extensively for wellhead/Xmas tree connections.

Seal replacement in vertical intermodule connectors would be a complex operation and, furthermore, the use of vertical connectors throughout a template could result in the stacking of modules which could preclude the individual retrievability of modules. The principal means of physically obviating this would necessitate the inclusion of a substantially greater number of bends in template piping systems and as such would be generally unacceptable. However, in a vertically stacked arrangement the philosophy of independent module retrieval need not be seriously compromised provided that the reliability of the lower modules is significantly greater than that of the

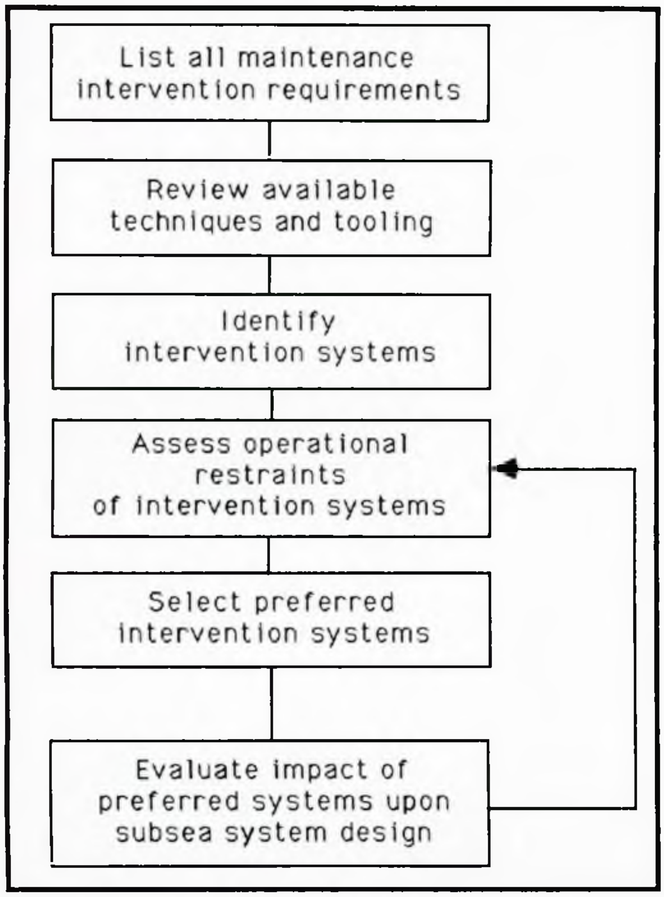


Fig 4: Methodology for establishment of maintenance intervention philosophy

upper modules. Risk of damage to up-facing connector hubs from dropped objects, and to seal surfaces from landing a module heavily, is higher for vertical connectors, and if two or more multibore hubs are to be mated simultaneously, the tolerance requirements become extremely onerous.

Summarising, although horizontal multibore connectors can have potential advantages over vertical connectors, the latter are field proven in subsea Xmas tree service and each application within a subsea system design must therefore be considered carefully with respect to implications on module size and piping arrangement.

In situ maintenance

An alternative approach is to develop the subsea production system such that individual components can be repaired *in situ*. Remotely controlled manipulation systems are utilised for this purpose, but subsea equipment must in most cases be relatively small and specially designed to facilitate effective repair/replacement by such means. By way of example, insert-type valves are utilised on the Central Cormorant UMC and are proposed for selected applications on the Esso EDIPS riser base manifold design.

Valve actuator replacement is generally considered to be a candidate for replacement *in situ* on other proposed deep water subsea production systems.

Encapsulated systems

Commercial encapsulated subsea completions and manifolds were pioneered by Lockheed Petroleum Services in the 1970s, and operated by Petrobras Offshore Brazil and in the Gulf of Mexico by Shell Oil, Union and Tenneco.

Such systems were developed at a time when deep water was considered to be of the order of 120 to 150 m; 1 atm systems tended to lose favour when diver depth capabilities improved in step with the development of ambient, wet subsea production systems.

This notwithstanding, small 1 atm encapsulation units are currently utilised on deep water multiplexed electrohydraulic control system packages and may be considered in the future for complex subsea manifolding arrangements. These may be in association with wet Xmas tree arrangements, as proposed by Mobil in their revamped 'SEAL' SAS system, or may even be considered to accommodate complex sea bed processing and/or multi-phase pumping systems.

Repair of encapsulated subsea equipment can be effected either *in situ* by trained technicians or by surface retrieval via a service bell or submersible intervention system. Safety aspects of transferring man from the service system into sea bed enclosures is an issue requiring much investigation, especially in deep water.

In summary, a choice of design approach is therefore available, selection of which will be governed by specific functional requirements, perception of state-of-the-art with maintenance intervention systems and any oil company preferences.

However, irrespective of which design philosophy is adopted, the design of subsea equipment and maintenance intervention systems is an inseparable, interactive process and especially so for diverless water depths. Although general purpose maintenance tools could be selected, or special purpose tools developed for a particular subsea system, selection must be made early in the design process in order to avoid serious conflict later.

The range of intervention systems presented in Fig 3 is reproduced in Fig 5, on which typical applications are indicated, and from which examples of different intervention philosophies are briefly described below.

Examples of alternative maintenance intervention philosophies

Central Cormorant UMC

The UMC (see Fig 6) was designed to accommodate up to nine wells, each of which could be drilled directly through the UMC template, or drilled remotely as satellites which tie back to the UMC using flowlines and control umbilicals. This satellite well tie-in arrangement provided flexibility to accommodate reservoir size and shape uncertainties as development drilling proceeded. The UMC manifold was also designed to allow each of these nine wellbays to be configured either as an oil producer or water injector, each serviced by TFL.

The design philosophy, although allowing operational flexibility, required the use of many 3 inch gate, diverter and isolation valves. The 3 inch gate and diverter valves were remotely operated and maintained by replacement using the remote maintenance vehicle (RMV) (see Fig 7) which could replace up to three 3 inch valves in a single trip utilising a special tool and storage rack. Equipped with a different tool, the RMV could also operate the many 3 inch isolation valves which set the function of each wellbay.

Each wellbay and other functions, eg chemical injection and pigging, were controlled by dedicated control pods which were also maintained by replacement using the RMV which could change out up to two control pods on a single trip.

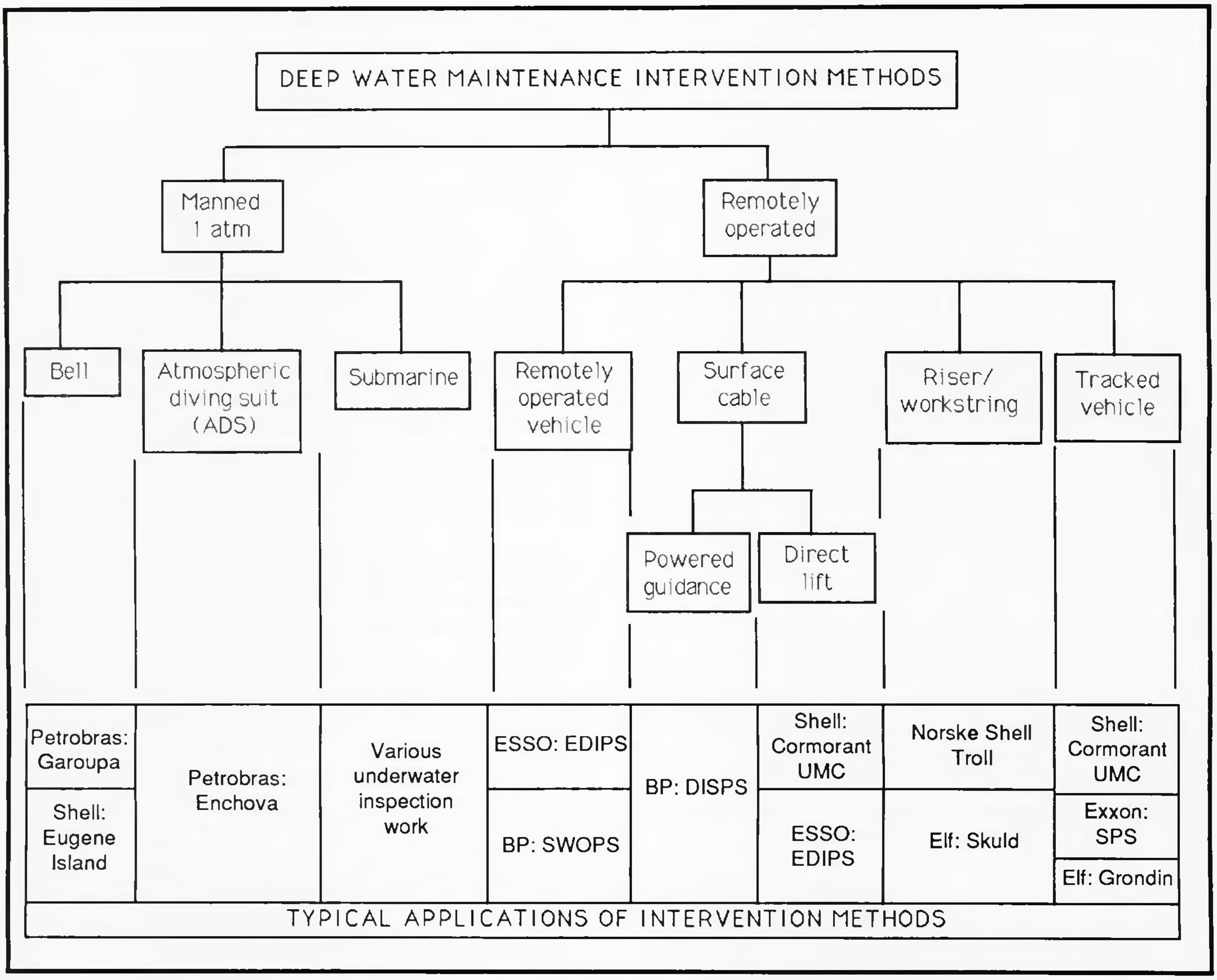


Fig 5: Typical applications of intervention methods

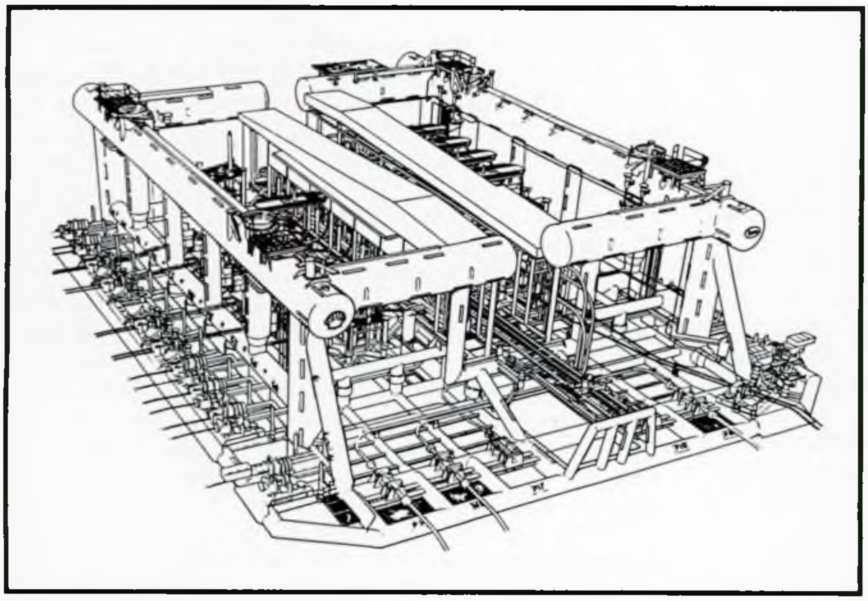


Fig 6: Central Cormorant underwater manifold centre

The intervention philosophy outlined above can be categorised as the replacement of individual components or maintenance *in situ*.

The UMC also incorporates equipment designed for surface retrieval. These include chemical injection units, hydraulic accumulator units, template Xmas trees and choke spools. These are recovered on guidelines using either a drillstring or surface lift line with specialist running tools to effect recovery and installation.

The selected design and maintenance philosophies are directly reflected in the shape of the UMC. The banks of 3 inch valves are mounted in two vertical racks, under protective roofs facing the central area which is clear except for the RMV track at deck level. This track and clear area extends through the top tubular structure to the RMV landing area on open space above the front porches, or flowline connection area.

The RMV is positively buoyant and hauls

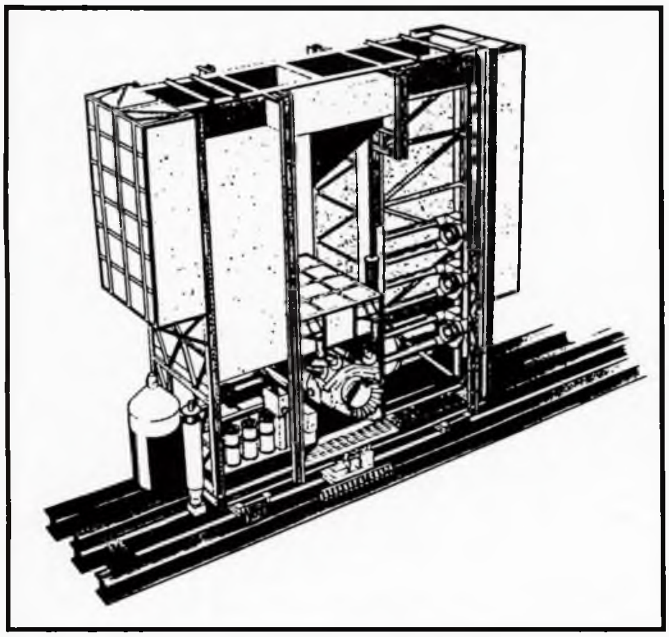


Fig 7: Remote maintenance vehicle

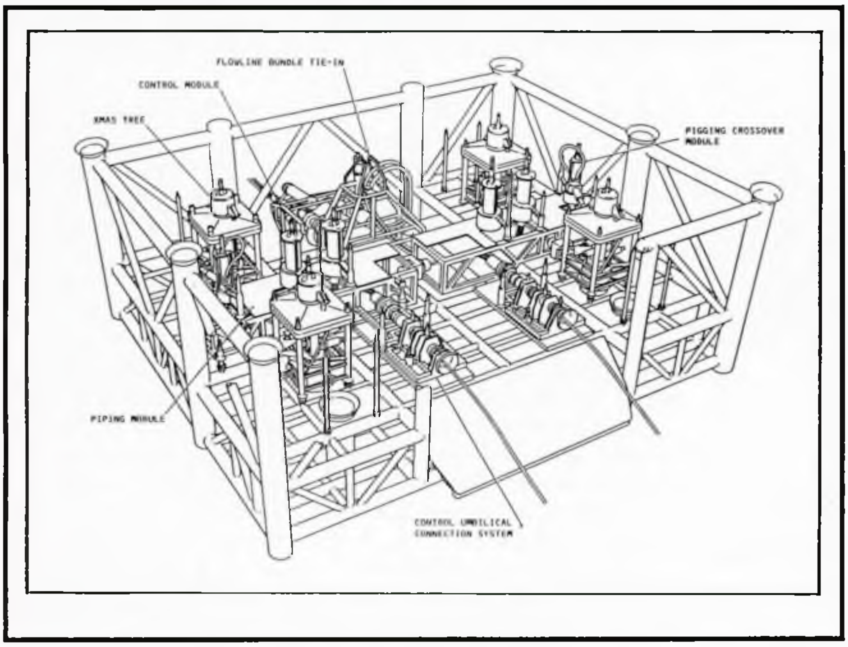


Fig 8: Norske Shell Troll field template

itself down to the landing area utilising an on-board winch.

Recoverable modules are contained in the area outboard of the manifold valve racks and inboard of the tubular protective fence. Space and navigation markers are provided to aid ROV access into the area for inspection. Pipeline and flowline porches are arranged outside the protective fence, and are set down close to the sea bed to facilitate flowline pull-in and connection.

From the foregoing description it is evident that many of the design features of the UMC are dictated by remote maintenance requirements.

Norske Shell Troll field

The subsea multi-well templates developed by Norske Shell for the Troll field (see Fig 8) are configured to facilitate independent surface retrieval of modules generally without the necessity to disturb other modules within the template.

This philosophy has resulted in the extensive utilisation of horizontal intermodule connections with the attendant ability to replace seal plates subsea, but with the drawback in terms of either having to provide additional flexibility within the template pipework or modules to make up the connector, or to develop new connectors with shorter make-up stroke requirements.

A schematic of a 4-well, wireline serviced oil production template is presented in Fig 9. In this particular design, the Xmas tree is very basic and comprises only those valves necessary to ensure the pressure integrity of, and vertical access to, the well, ie the master and swab valves. The 'working' valves of the system are incorporated within an easily retrievable adjacent valve module, which in this particular case is connected to both the Xmas tree and template piping module by means of horizontal connectors. Contained within the valve module are wing valves, cross-over valves, any requirements for chemical injection and a control module. (NB If required for particular applications, production chokes could also be incorporated within the valve module.)

The piping module provides a passive interconnection between the valve module and the flowline bundle connection and also serves to protect template pipework against dropped objects; all necessary flexibility is provided within the module to facilitate connection of the valve modules and flowlines.

Modules are, by and large, designed to be retrievable using a workstring intervention system, and are sized such that they could be run through the moonpool of a typical North Sea semi-submersible drilling rig. This approach obviates dependence upon a specially designed workover or maintenance vessel.

Contingency diverless backup is provided by arranging sufficient access space around the modules for a variety of ROVs or manned, 1 atm suits. In this way, flexibility is provided to incorporate the most appropriate backup means from the range of available systems.

A similar approach has been adopted for deployment of inspection equipment. The majority of inspection work can be performed using a small 'eyeball' ROV which can be deployed without the necessity to disturb equipment protection provisions.

BP DISPS

BP's Diverless Subsea Production System (DISPS) currently under development (see Fig 10) is designed for a 'base case' water depth of 400 m but with an understanding of system implications down to 750 m. The basic design premise is that all equipment maintenance will take place on the surface and to this end equipment is configured in interconnecting modules for retrieval. Maintenance and intervention requirements were dominant factors in the generation of modularisation philosophy. The arrangement of modules and components were dictated both by the desired degree of independence of module retrieval and by the perceived frequency of operation of components and their reliability. Horizontal connections are therefore utilised where independent module retrieval was desirable, eg Xmas tree/valve module connections, whereas

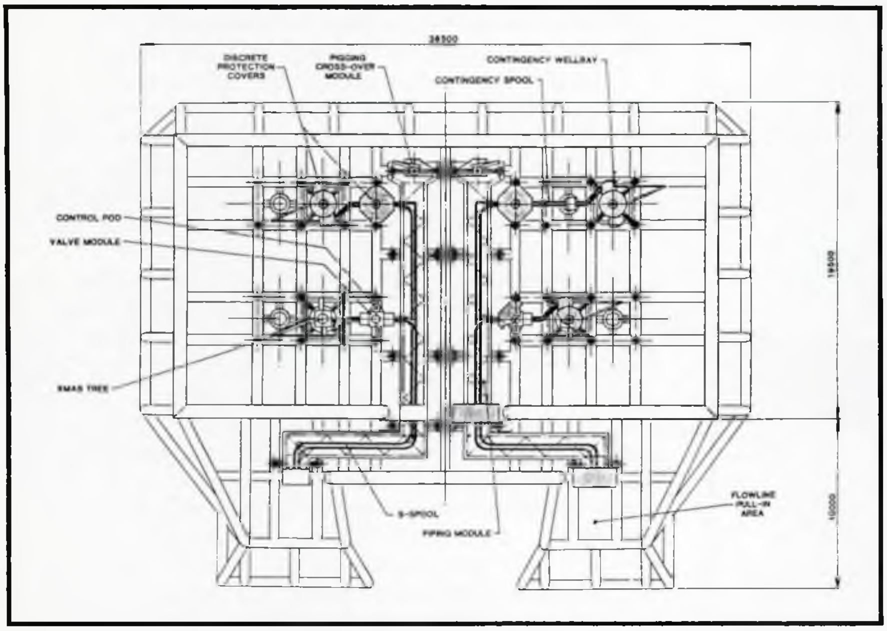


Fig 9: Plan view of multi-well template design

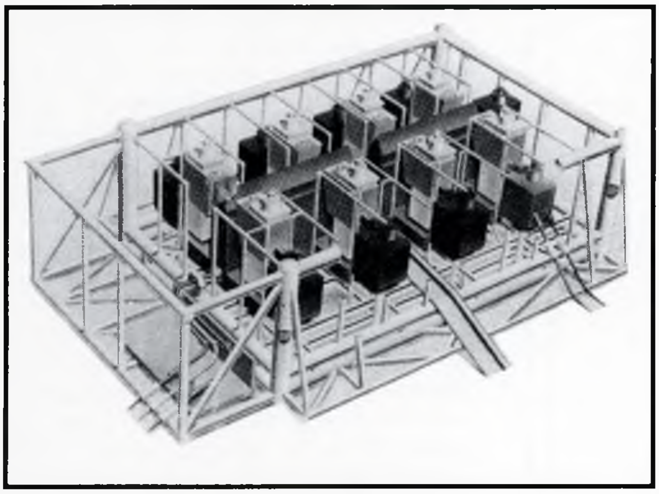


Fig 10: BP diverless subsea production system (DISPS)

production valve modules are vertically stacked, as indicated in Fig 11. Modules containing the most active and/or statistically least reliable components are located uppermost in the stack and those containing either no active components, or which would rarely be utilised, at the bottom.

The improved system cost-effectiveness achieved by minimising the size of individual modules and the overall template size through the vertical stacking of modules is considered to outweigh the negative impact on maintainability resulting from entrapping modules within and beneath the valve module stack-up.

When required, maintenance is conducted by guidelineless module retrieval, which is achieved by deploying a lift wire and thruster pack/running tool unit through the moonpool of a monohull vessel, the thruster pack providing coarse guidance of the module relative to the template structure. Final guidance is achieved via interlocking guidance structures integral with the modules and the template structure. All modules for which retrieval is anticipated during the life of the template can be retrieved and replaced in this way. Larger passive modules, which would only be retrieved in the event of unforeseen damage, would be retrieved by conventional lifting techniques, but again without guidewires, the structures themselves providing the necessary guidance.

ROV activities are restricted primarily to inspection or override/backup tasks, in particular the overriding of valve actuators and horizontal connectors. However, template design is such that ROVs can access all critical components via well-defined access corridors. In this way an ROV can be used in the event of a totally unforeseen problem.

Esso EDIPS

Central to the Esso Deepwater Integrated Production System (EDIPS) is a deep water (610 to 1070 m) remotely maintained manifold located at the base of a SALM (single anchor leg mooring) riser to which a ship shaped production vessel is moored. The manifold is designed to fulfil several functions within a hypothetical field scenario, the purpose of which was to develop potential building blocks of a total system which could be integrated in various combinations to suit specific field requirements. These functions include:

1. commingling produced fluids from subsea wells;
2. distributing high pressure gas to subsea wells;
3. distributing high pressure water to subsea wells and a tension leg platform (TLP);
4. distributing TFL tooling for subsea well maintenance;
5. exporting medium pressure gas to a TLP;
6. importing dead crude from a TLP.

Maintenance philosophy of the riser base manifold (see Fig 12) is similar to that employed on the UMC. Small valves and control modules are replaceable by ROV as individual components, while larger components, such as 12 inch shut-off valves and the control distribution module, are retrieved on guidelines with a surface lift line and running tools. The use of guidelines rather than guidelineless techniques at these water depths was dictated by the proximity of the SALM, it being essential to safeguard against heavy modules (up to 35 tonnes) impacting the SALM.

The EDIPS manifold represents a different approach to ROV maintenance from that employed on the UMC. Valves and control pods are retrievable by several commercially available ROVs utilising special tool packages. Although a tracked vehicle could be considered in specific circumstances, the refinement of the original subsea production system/UMC maintenance concept via the Exxon, Zinc Field program, to the current EDIPS concept, offers a component maintenance system which is effective in both deep water and diver depths. A typical tool package design for retrieving the 3 inch insert valve is presented in Fig 13.

The influence of maintenance requirements on the manifold design is very strong. Vertical racks located either side of the manifold (see Fig 12) contain 3 inch valves which would be accessed horizontally by ROV for valve replacement. The valves face outward so that the ROV is provided with direct unimpeded access. Guideline retrievable components and modules are located in the central area of the manifold between the valve racks.

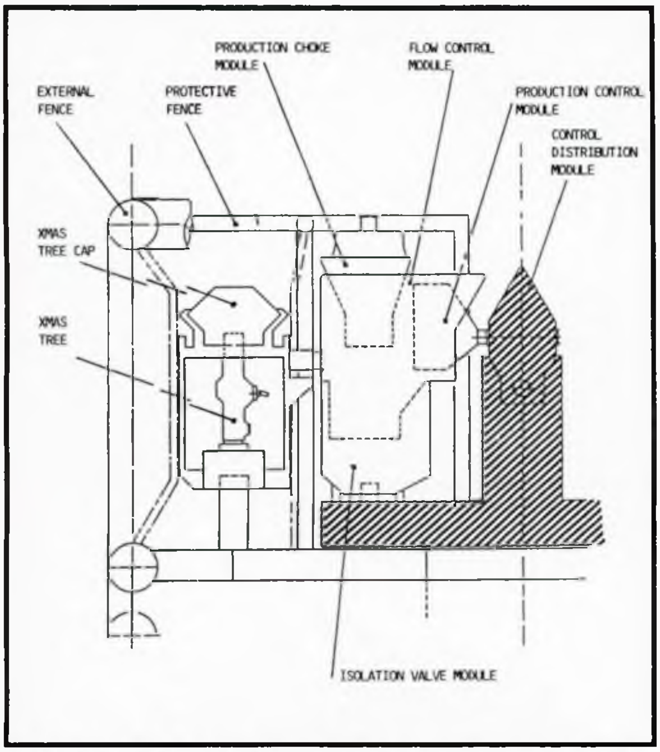


Fig 11: Schematic diagram of module arrangement

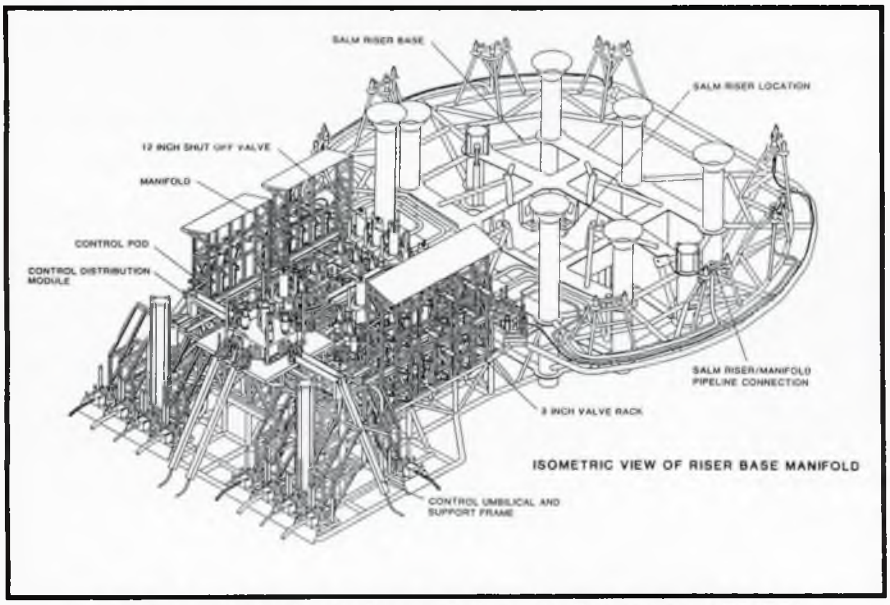


Fig 12: Esso deepwater integrated production system (EDIPS)

For initial installation it was important to minimise overall weight, which in practice resulted in the need to be economical with space. The central area of the manifold is thereby relatively congested, containing remotely operated valves, ROV-operated valves and complex pipe runs; to ensure adequate access for ROVs for setting guidelines, inspection and isolation valve operation, the complete manifold was modelled on computer-aided design (see Fig 14). A feature of the central area is the control distribution module raised high on the manifold to provide clear ROV access for control pod replacement.

The EDIPS manifold is a further example of the impact of maintenance philosophy on subsea systems design.

Petrobras Garoupa field

The Garoupa subsea production system (see Fig 15) comprised a 1 atm dry manifold centre configured to commingle produced oil from seven outlying wellheads, which were also contained within 1 atm dry wellhead cellars.

When installed, the system was the world's deepest subsea system, installed water depths ranging between 120 and 160 m. Flow from the wellhead collars was commingled in the manifold centre and exported to a process platform.

The overall system was designed by Lockheed Petroleum Services (LPS) and fabricated by LPS in Vancouver and Ishibras in Rio de Janeiro.

The manifold centre incorporated production chokes, a test header, corrosion inhibitor injection arrangements, in addition to provisions for pigging and gas lift. It also served as a relay station between the platform-based control station and the subsea well completions.

Interconnecting flowlines between the manifold centre and wellhead cellars, being first and second end connections respectively, were pulled into ports on each enclosure, without diver assistance.

All production equipment was stored within the respective wellhead cellars during installation for later commissioning by trained technicians.

Each wellhead cellar and the manifold centre was provided with a 'teacup' onto which the positively buoyant, 1 atm service bell could haul down and land to enable manned intervention at atmospheric pressure. The service bell was deployed over the stern of a special service vessel (see Fig 16). The service vessel was basically a converted North Sea-type supply vessel fitted with an overstern 'A' frame and fitted-out to provide all life support and other services, via an umbilical, to the service bell and, with the bell docked onto the subsea installations, into the 1 atm enclosures.

In normal operational conditions the 1 atm enclosures were inerted with nitrogen-rich air in order to prevent the accumulation of a combustible atmosphere. During short maintenance intervention visits, crew transferring from the service bell to the sea bed enclosures used a mask system to avoid lengthy cleaning and reinerting of the atmosphere.

Although the 1 atm system operated efficiently once unrelated downhole problems had been rectified, such systems have, by and large, been superseded by advances in ambient wet subsea production technology which, in deep water designs, eliminate the necessity for man to operate in potentially hazardous conditions subsea.

CONCLUSIONS

This paper has highlighted that no two oil companies adopt identical approaches to diverless system design although some similarities do exist. Therefore, any discussion on the merits and demerits of alternative philosophies for the design of diverless subsea production systems must be considered in the light of the particular application and the fact that there can be several near-optimal solutions to any given problem.

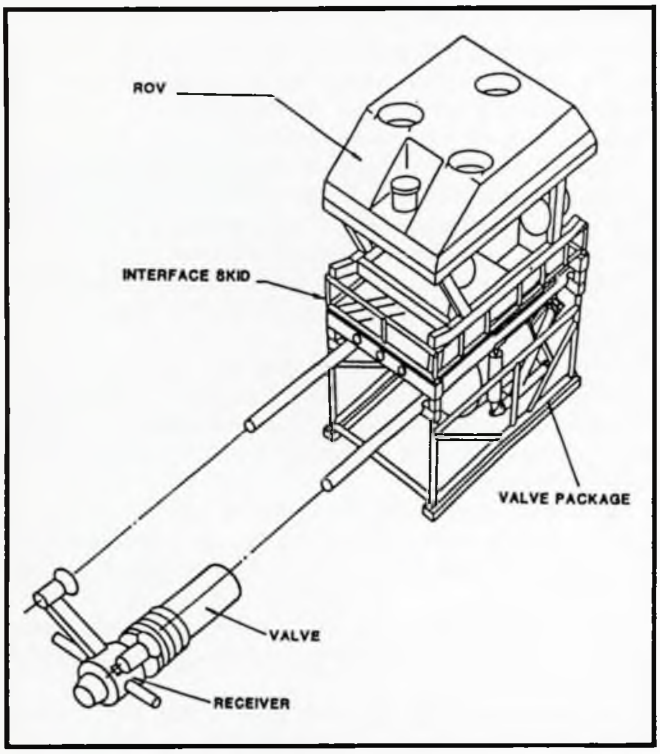


Fig 13: ROV package

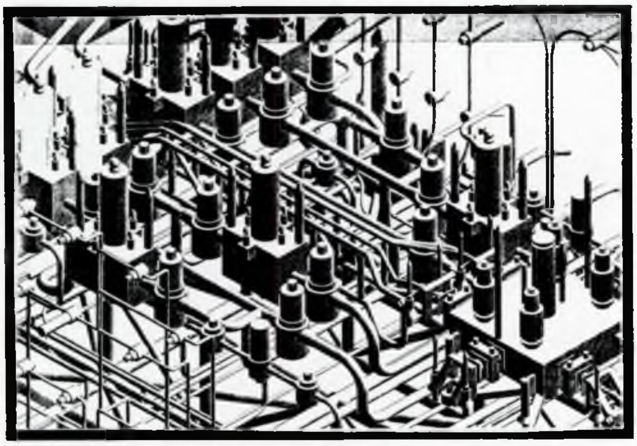


Fig 14: CAD presentation of valve arrangement

An interesting point is that even within the same company major variations in philosophy can exist; by way of example:

1. Shell Oil pioneered the development of 1 atm production systems in the Gulf of Mexico;
2. Shell Expro, as operator of the Cormorant Field, designed the UMC in collaboration with Esso, in which primary maintenance was effected by means of a tracked RMV;
3. Norske Shell has developed the Troll Field templates, based on a retrievable module design philosophy.

It is interesting to note that in establishing the preferred design philosophy for Troll, Norske Shell fully considered all aspects of Shell Group experience, including developments mentioned above. Therefore, in recognition of this, factors which tend to dictate the approach adopted are:

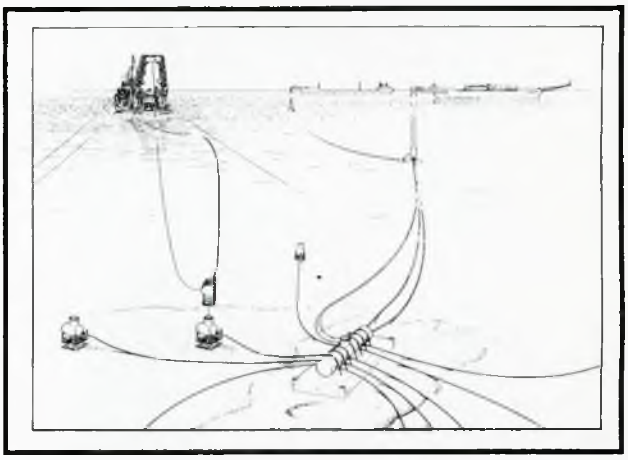


Fig 15: Petrobras Garoupa subsea production system

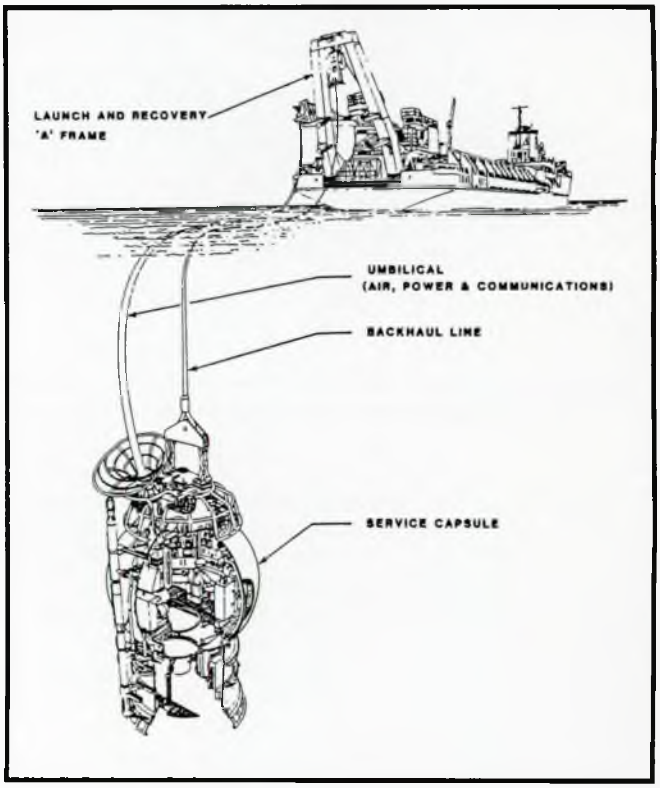


Fig 16: 1 atm service system

1. size and location of field;
2. timing of development;
3. state-of-the-art of technology;
4. type of application;
5. previous experience of operator.

Systems presented in this paper which have the greatest commonality are:

1. BP DISPS;
2. Elf Skuld (East Frigg);
3. Norske Shell Troll.

Of these, DISPS and Skuld adopt very similar modular configurations, which are based predominantly on the vertical stacking of modules. The Troll Field template design is based mainly on horizontally connected modules.

In both DISPS and Troll the fundamental requirement to provide independence of retrieval of the Xmas tree and valve module(s) is achieved by the use of a horizontal connector between the Xmas tree and the valve module. In the case of DISPS, however, the fact that flow is commingled and alternative services must also be provided for each well (ie production, test, gas lift or water injection) creates complex requirements for the valve module in addition to a need to provide isolation from the manifold headers. The valve module stack is split vertically into three separate modules, the lowest of which simply provides isolation from the manifold headers. The two top modules provide all functions associated with a particular wellbay, with the uppermost module containing the lowest reliability/highest utilisation components such as a production choke and flow control valve to allow easy retrieval. In operation, the two 'active' modules could either be removed separately or as a single unit.

A horizontal connector arrangement would result in the template plan area increasing significantly and would introduce a requirement to provide sufficient pipe flexibility to cater for horizontal connector stroke requirements. In the case of Troll, which has no commingling, valve module design requirements are significantly simpler and therefore allow the use of a single valve module; the use of horizontal connections to the piping module is thereby rendered practicable.

Both approaches are equally acceptable within the context of the system and application requirements, with template size considerations in the case of DISPS far outweighing any maintenance limitations imposed by vertical stacking of modules.

A second fundamental difference between Troll and DISPS is the use of guidelines and workstring for intervention in the former and guidelineless techniques with a thruster pack in the latter. In the case of Troll the design is geared to a specific application in 340 m of water, well within guideline capabilities, whereas DISPS is targetted for water depths down to 750 m, which is on the limit of guideline capability, thereby making the guidelineless approach more attractive despite the intrinsic risk of damage during intervention operations. This particular problem has been addressed by providing protection fences between each module stack/wellbay. Therefore, again Troll and DISPS are each designed to meet different requirements.

In modular subsea system designs such as Troll and DISPS, the decision is taken to retrieve complete packages, even if only a single component within the module has failed. The Esso EDIPS philosophy, however, is currently not to use production equipment modules (except Xmas trees) on the basis that in retrieving a failed component, it is preferable not to disturb other equipment which is functioning normally. This approach also has its merits, especially when the module retrieval philosophy necessitates breaking and re-making large connectors complete with multi-bore seal arrangements.

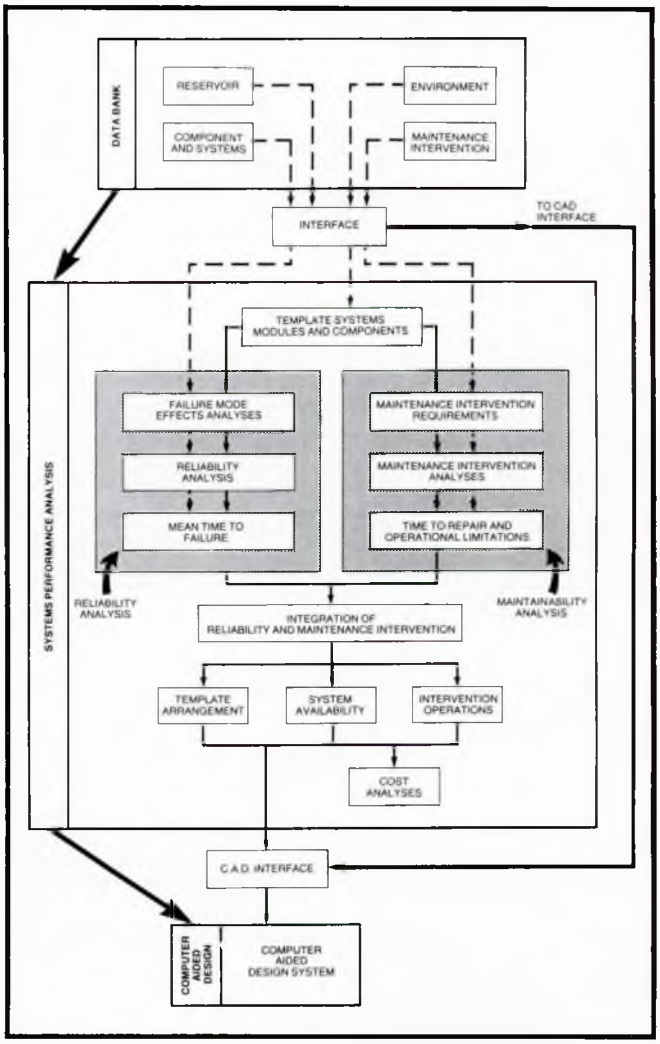


Fig 17: Operations simulation of template/manifold system

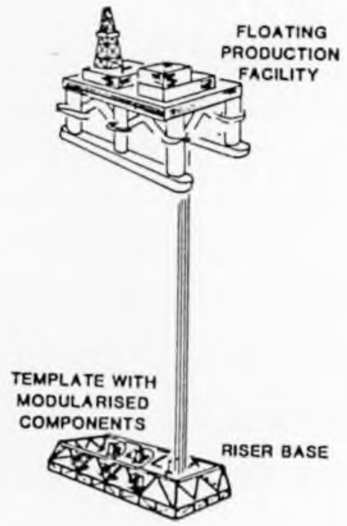
The single-component retrieval philosophy does, however, impose some different constraints on subsea systems design, for example:

1. the major impact of a tracked vehicle on the UMC design;
2. accurately controlled intervention arrangements required to effect component retrieval from within congested areas;
3. greater potential risk of damage to non-retrievable interfaces during intervention operations.

The final system considered is the dry, 1 atm system. Currently, Mobil is developing an advanced SAS (ex-SEAL) system which comprises a template system with diverless, wet Xmas trees connected into a dry, 1 atm manifold centre. Possible applications for such systems, in various configurations, are:

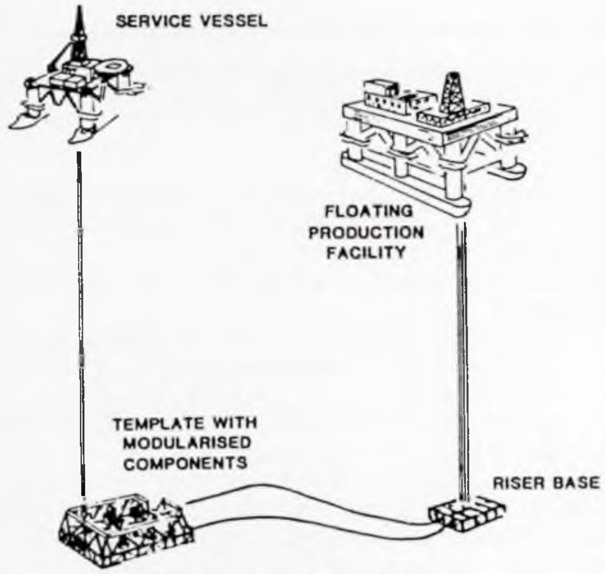
1. complex manifold arrangements;
2. accommodating processing and other production systems, possibly for sub-ice operations;
3. housing multi-phase pumping equipment and associated control arrangements.

However, the emotive aspect of transferring man into confined sea bed enclosures in deep water and exposed locations must be overcome. Also, from a safety standpoint it is probable that diverless intervention systems can be more readily



TEMPLATE ACCESSIBLE FROM FLOATING PRODUCTION FACILITY

OPTION 1



TEMPLATE REMOTE FROM FLOATING PRODUCTION FACILITY. SEPARATE SERVICE VESSEL FOR MAINTENANCE ACTIVITIES.

OPTION 2

Fig 18: Seabed location options for template/manifold system

deployed in higher sea states than manned intervention vehicles.

Therefore, the 1 atm approach has currently been overtaken by state-of-the-art diverless systems and, as such, seems destined only for specialised applications in the future.

On balance, all of the systems described can be effectively designed to meet deep water production requirements, but the impact of maintenance intervention on all aspects of design must be seriously addressed throughout the design phases.

Basis for subsea production concept selection

Typically, most subsea production system developments commence with a preliminary conceptual design phase during which a wide range of system variations are generated. Even after eliminating the less acceptable options, several feasible alternatives often still remain. It then becomes necessary to select preferred arrangements from the numerous available permutations, and to assess these after elementary detailing.

In the vast majority of cases, a ranking procedure is employed which is basically performed by members of the project team estimating the relative merits of particular subsystems, methods and features of the proposed subsea configurations. After weighting scores assigned to the elements under review, a contender considered worthy of further development is identified. The entire evaluation is qualitative and analysis is seldom conducted in support of the final decision.

Decisions made at this stage can have a most profound effect upon the entire field development and there is therefore a need to conduct more accurate, quantitative predictions of all important facets of design and offshore operations in order to provide a more definitive method of identifying an optimum concept, prior to undertaking detailed design.

Subsystems of a subsea production system can be modelled and simulated by computer, in order to assess production availability and sensitivity, whilst taking cognizance of: equipment layout and reliability; production and intervention philosophies; essential services and statutory regulations. In the simulation, control can be effected over all parameters modelled and changes made to obtain required performance objectives. It is thereby possible to optimise a subsea production system with respect to establishing maximum efficiency of equipment and resources with minimum costs and maximum returns on capital invested in a field development.

A flow diagram of the simulation of a subsea production template/manifold system is presented in Fig 17. A similar simulation program was used extensively in the development of the subsea production facilities for the Troll Field; a similar but more rudimentary method was applied to DISPS.

Table I: Effect of subsea equipment location production availability

Field development option	*Maintenance support vessel*	*Mobilization time (days)*	*Production availability (%)*
Option 1	FPF with workover	0	78
	FPF without workover	3	75
Option 2	Dedicated	3	75
	Separate	15	67
	(Hired)	30	55

The results of such programs are the confidential property of the respective oil companies. Therefore, a typical example of a non-site-specific application of simulation techniques to assess the impact of subsea maintenance activities on floating production facilities in deep water is summarised below.

Typical application of field operations simulation

Subsea maintenance intervention requirements can have a major impact upon the design of a floating production facility and, in the ultimate analysis, on field economics.

The sea bed location of a multi-well template in relation to a floating production facility can influence subsea maintenance intervention operations, topside space and load requirements on the floating production facility, and field production availability. These aspects have been addressed by analysing field operations in detail by means of computer simulation techniques (see Fig 18: example presented in OTC 4789; Impact of Subsea Maintenance Activities on Floating Production Systems in Deep Water).

In this example, the subsea intervention requirements of a state-of-the-art wireline-serviced modular template similar to that illustrated in Fig 8, have been evaluated in order to assess the potential impact upon a floating production facility and field economics. A methodology essentially similar to that presented in Fig 17 was followed in order to analyse reliability and maintainability aspects of the subsea template design.

The best data available on the reliability of subsea components and systems should be utilised; in some cases this would be actual information on field proven equipment, but in other cases estimated reliabilities or data from non-oil industry sources must be utilised. When the purpose of the simulation is to evaluate the sensitivity of various options within a particular subsea system design, or to assess alternative sea bed locations for the template, absolute accuracy of reliability data is less crucial.

An important aspect of the simulation is the evaluation of template system maintainability. Input data into the model will be actual estimates of all maintenance activities likely to be required, and the weather and other restraints which can impact the ability to undertake them.

The simulation was performed against a field life of 20 years and the following assumptions.

1. Template production shutdown would be required during sub-surface safety valve and Xmas tree replacement. Only the nominal capacity of the associated well would be lost during replacement operations on other modules.
2. Module failure distribution is exponential; failures based upon module life *in situ* and not actual production life.
3. Module repair distribution is log-normal; specified mobilisation times for support vessels do not apply when a vessel is already on location.

Summarised results of the computer simulation are presented in Table I, which highlights that the preferred template location would be directly beneath the production facility.

Production availability would be reduced from a maximum of 78 % when the subsea template wells can be directly accessed from the floating production facility, to 55 % with a remote template with a 30 day mobilisation requirement for a separate, contract-hired support vessel. Similarly, the lack of a full subsea well workover capability on the floating production facility would result in a reduction of production availability from 78 % to approx 60 %.

These reductions in availability must be viewed against the impact of subsea maintenance intervention equipment upon vessel topside layout and payload. Provision of a workover capability, in particular, introduces approx 1000 tons of additional equipment requiring up to 1200 m^2 deck space. This system would, however, be able to undertake all module replacement operations, in addition to downhole remedial work.

In conclusion, therefore, this example demonstrates that the provision of subsea maintenance intervention equipment on a floating production facility can have a significant bearing on the economic viability of a field development, but this must be traded against topside payload.

THE WAY FORWARD

In meeting the challenge of developing subsea production systems for deep water applications it has been necessary to apply a greater level of systems engineering than hitherto considered, and to draw upon engineering techniques and standards developed and proven in the aerospace, warship design and nuclear power industries.

Major subsea systems, such as multi-well template/manifolds, have become highly systems engineering-intensive in order to achieve greater reliability than earlier subsea systems coupled with ensuring that maintenance intervention can be effectively performed entirely without diver intervention. Component reliability must be achieved through good, simple design combined with the application of effective quality assurance procedures. Maintenance and equipment design philosophies must be tailored to provide the optimum solution for specific applications and not become restricted by company philosophies.

Overall cost-effectiveness of subsea production systems can only be established by evaluating the subsea hardware and all associated support equipment necessary to install and maintain production equipment throughout its working life.

Detailed evaluation of reliability and maintainability has been addressed in other industries for several decades. Furthermore, by application of computer simulation techniques, reliability and maintainability considerations can provide a satisfactory basis against which various optional design arrangements, systems and components can be thoroughly evaluated in order to identify an optimum arrangement which provides the maximum availability from the production system.

Again, computer simulation techniques have been utilised extensively in other industries. By way of example, all relevant design and operational parameters of the main propulsion installation, and the ships hull of modern high-performance warships, powered by a combination of gas turbines or gas turbines and diesel engines, are dynamically simulated and the sensitivity of various key parameters assessed against different control philosophies and characteristics. Without undertaking computer simulation, it would not be possible to establish the control requirements of such installations, under onerous operational states, which would provide optimum dynamic response, and hence fighting efficiency of the ship, without violating such design constraints as shaft torque and thrust, or resulting in gas turbine overspeed or stall.

The fighting efficiency of a warship is directly analogous to the production availability of a subsea production system. By employing simulation techniques it is possible to identify areas in which reliability and maintainability can be improved and to thereby attain greater production efficiencies from subsea systems.

Deep water subsea production facility design has involved more up-front design engineering than most current shallow water designs. It may be argued that initial expense incurred in conducting initial simulation, design optimisation and conceptual design work would have a deleterious effect on cash flow, being conducted so early in the field development program. However, savings made by preventing a single major failure of the subsea production system, potentially resulting in protracted shutdown, would more than compensate for the additional up-front cost, which would be almost negligible by comparison.

With oil prices significantly lower today than a few years ago, many more offshore fields can now be classified as marginal. The application of 'deep water' systems design rationale would undoubtedly improve the rate of return on capital invested in the development and operation of marginal developments in any water depth.

ACKNOWLEDGEMENTS

The Author gratefully acknowledges the assistance provided by his senior colleagues, Peter Metcalf and John White, Project Managers on BP DISPS and Esso EDIPS projects respectively.

Discussion

I M Barrett (The Marine Technology Directorate Ltd) I should like to congratulate Mr Adamson not only on the comprehensive survey of the subject of subsea production technology, but also on the excellent standard of the presentation. There are several points which I would like to highlight.

The recent decline in the price of crude oil coupled with a serious possibility that the low price scenario may continue for a considerable period, perhaps to the turn of the century, poses the problem of how continuity of technological capability will be maintained over the next 10 years.

Long haul crude may well be the preferred option over new offshore development although cost-effective marginal field production will continue to be stressed. As a result, there will almost inevitably be a downturn in the number of projects starting in the area of subsea production which will cause very rapid withdrawal of firms from this business sector which has never yet achieved maturity in the commercial sense.

Such a climate is favourable neither to continuity of staff nor to skills and yet it is right now that UK industry in particular should be preparing a viable industrial capability to avoid missing the second chance to establish a strong commercial capability in the subsea manufacturing, fabrication and service sectors.

It is vital that the underlying technology behind the rapid developments made in subsea production since the 1960s is passed on to the next generation of engineers. In turn, this demands an availability of engineers equipped with the necessary multidisciplinary skills if understanding of the progress in subsea technology made since the mid 1960s is to be retained.

In summary, we must act now on the training required to ensure that the oil industry's future subsea needs will be adequately met.

The use of European Grant and loan funding, despite the reputedly large additional paperwork required, should be pursued to establish the necessary new facilities and test programmes as well as to assist in training aspects. Award of support is becoming more dependent upon applications showing an element of European Community transnational co-operation to meet the prime conditions of the schemes.

In his presentation, Mr Adamson compared the subsea equipment industry with that of warship building. I concur and lament that this was recognised in 1974 when discussions were held with the warship builders pointing out to the management the opportunities in the offshore industry that they were in an excellent position to take up. Not a lot happened and today I can only repeat that I hope that the second opportunity will not pass unheeded.

On a more technical point, it should be stressed that the subsea production techniques described are elements which may be employed in association with others to permit the most appropriate production scheme to be developed for the specific requirements of particular oil or gas field. Thus, although we may expect to see familiar small fields using subsea production coupled to existing facilities on a platform for instance, there will also be a considerable market in producing short-life fields with re-usable systems such as tanker based floating production vessels for instances.

S M Adamson (Fuel Subsea Engineering Ltd) I greatly appreciate Mr Barrett's congratulations on my paper.

Mr Barrett's comments of the parlous economic state of many offshore developments, and the impact this is having on both the number of live projects and production methods, are indeed extremely valid. A major ramification of this is, of course, the serious problem of recruiting and retaining suitable qualified engineering personnel. As I stated in the introduction to my talk, this was one of the reasons why I was 'persuaded' by Mr Sloggett (Secretary, IMarE) to write my paper. By so doing I hope that I have offered encouragement to members of IMarE and RINA to become somewhat less parochial and to direct their very relevant talents to the present marine technology dominated oil and gas industry.

I do, however, have some major reservations on the question of using EC grants to promulgate training, and the development of new facilities for the oil industry. The basis upon which grants are now awarded is significantly more onerous than it was in the past. Whereas EC bureaucrats state that it is their primary intention that smaller companies should be supported, the long delay in providing funds and the associated commercial terms are such that, by and large, only larger companies can afford to rely upon such support to initiate new projects.

In addressing my paper to Mr Barrett, I was obviously preaching to the converted. Like him, I hope that the oil industry will see the benefits of, and endeavour to utilise, technological capabilities available in other, in some cases, declining industries.

I concur with Mr Barrett's statement that a market exists for stand-alone floating production facilities, especially where small accumulations of oil are located too distant from existing field production infrastructures. I particularly support his view that ship shaped production vessels, allied to subsea completions, offer considerable potential. Development programs and live field developments undertaken since 1974 based on this type of system demonstrate their technical and economic viability in most offshore operating environments.

A Burnett (Offshore and Marine International Services) I would first like to welcome this excellent paper aimed mainly at those with little or no knowledge of the subsea international offshore marketplace.

The remarks in the beginning of the Conclusions section of the paper are so true of this complete industry, but yet are very rarely appreciated by those trying to gain a market share for their products and services.

All international operators and contractors have different ways of providing solutions to offshore field development, and to a great extent these solutions are influenced by the fact that no two development programmes can possibly be the same, largely because of the different size and location of the fields, different water depths, different distances from land, different oil/gas/mineral contents, different political and environmental considerations, etc.

The paper, whilst referring to certain international events, does not emphasize the difficulty that any development, wherever in the world it takes place, will have a bearing on the solution of the development programmes in other part of the world and that the North Sea (UK, Norway, Denmark, etc) developments are not necessarily the panacea.

Whilst the paper addresses primarily diverless development programmes, it must never be forgotten that development of diving techniques is still going on and that new mixtures of hydrogen, oxygen and helium gases are now making it possible to dive to depths of 800 m or more. The question always remains – how can cost-effective work by carried out subsea? By diver look out? By deep water diving? By diverless means? – there is as yet no clear answer and therefore, whilst diverless work programmes are important, they are not necessarily the most cost-effective way of doing the job.

The paper addresses subsea manifolds, templates and the like. Again it must be remembered that there are other ways of producing from subsea wells in deep water, such as well TLP and FPS development programmes. Again little mention is made of the possible use of autonomous offshore manned submarines fitted out with a variety of underwater work tools and other gear for subsea work programmes. The offshore market is made up of a variety of work systems for solving similar problems.

Another matter, not always fully appreciated by those outside or on the fringe of the international offshore market, is that there are worrying shortages of properly/fully trained technical personnel at all levels in the industry. An operator (eg an oil company) cannot achieve the optimum cost-effective methods of providing himself with an adequate return on his ideas/investment within the time-scale required, without full and adequate technical support from industry at large. This will not be fully forthcoming without the recognition, followed by active corrective programmes, of the general lack of adequately trained technical personnel at all levels (contractors and supply/service companies) within most of the industry at large. This industry has also vastly increased its maritime content since the early days in the Gulf of Mexico – their maritime content needs maritime awareness followed by maritime based solutions.

The paper has referred to a number of the current problems for subsea development. These problems are continually changing as new and varied solutions become proven and available for use. Therefore there must be a strong and well-directed R&D and test programme at all levels in order to provide the industry with suitable, reliable and cost-effective solutions to the ever-changing needs. This is difficult and costly, but has to be addressed. Reliability, as mentioned in the paper, is vital.

Mention has been made of computer and simulation programmes to aid the design and development work programmes. This is often dangerous ground because unless sufficient and proven data is fed into the computer programmes, it will not be possible to achieve good results. This does not mean to say that these programmes should not be tried, but that care must be taken with the result/output.

There was not a great deal of information in the paper about the way forward. It is suggested that the following points, amongst many others, should be addressed.

1. The use of expert systems to aid design and development.
2. The possible incorporation of subsea separation and multiphase pumping modules in the subsea production programme of the future.
3. The increased use of new materials such as composites both to reduce the initial price and maintenance costs (eg corrosion).

In conclusion, the author has made some valuable information available to marine engineers, and hopefully these maritime challenges of the subsea international offshore industry will encourage more marine engineers to offer their skills to this growing industry worldwide.

S M Adamson (Fuel Subsea Engineering Ltd) I acknowledge Mr Burnett's extensive range of comments on the paper in the spirit in which I believe they were intended and trust that he will accept my response in similar vein!

In response to Mr Burnett's opening statement, I should like to emphasise that the intent of the paper was to provide a technological treatise on diverless subsea production systems, and to highlight synergy between design requirements of such systems and technology and design techniques adopted by other industries. The paper provides a considerable amount of information on state-of-the-art subsea systems of types which may become more prevalent in future. Therefore, contrary to Mr Burnett's suggestion, the paper will be of value to experienced subsea engineers currently working on basic diver installed and maintained subsea systems and also to engineers from other industries interested in career diversification into the oil industry.

Mr Burnett's statement regarding 'international events' is somewhat baffling. Against a background of describing salient technical details of systems developed for operation in UK, Norway, Brazil, Gulf of Mexico and Canada, the paper sets out to define a practical systems engineering design methodology to facilitate the development of reliable and cost effective subsea systems, irrespective of geographical location. The paper specifically does not advocate a particular design solution for all developments – in fact it proposes precisely the contrary.

Reference to utilisation of divers in deep water was covered in the paper and emphasised in the presentation. The key issue here is the water depth at which saturation diving is not, and may never become, a routine operation. Specifically on this issue, a major international diving contractor considers ROV intervention to be more cost effective than diver intervention at water depths greater than 200 m. On the oil company side, Statoil concurs with this view and some UK based operators are currently evaluating a subsea maintenance philosophy in which equipment is design for routine maintenance by ROV, with saturation diver back-up for unplanned events. It is my personal view that it is futile to even contemplate employing divers as the primary means of maintenance in 800 m water depth, as implied by Mr Burnett. Given the current investigations into serious health hazards emanating from saturation diving in current, comparatively shallow water depths, deep water diving trials conducted under highly controlled conditions cannot be accepted as a meaningful basis for the design of commercial subsea production systems in ultra-deep water.

In response to Mr Burnett's general points on 'other means of producing from subsea wells in deep water', the design rationale proposed in the paper has been adopted by some operators and is applicable to almost any field development scenario in which subsea production equipment is utilised, including systems tied back to floating production terminals. In case of TLPs, Xmas trees would generally be installed on the platform although in some cases, including shallow reservoirs in deep water, it may also be necessary to tie additional satellite wells, completed subsea, back to the TLP. Therefore, subsea production systems are complimentary, and not an alternative, to the other means mentioned by Mr Burnett.

Reference to the use of autonomous manned submersibles in the paper was limited to a degree consistent with their suitability for intervention work on the type of systems addressed in the paper. Generally, the alternative methods described are more suitable, more readily available and cost effective for intervention tasks on subsea production equipment.

With reference to Mr Burnett's point promoting R&D programs to enhance the industry's ability to resolve technical problems, I believe that the need for fundamental research has diminished in comparison with industry needs about 8–10 years ago. I do however agree that practical development programs are required, but that these must be focussed directly on the resolution of real problems, culminating in meaningful improvements in the overall economics of offshore field development.

Mr Burnett's statement on the application of simulation techniques is somewhat overtaken by events in the oil and gas and defence industries. As described in the paper, and emphasised in the presentation, such techniques have been an indispensable design tool for decades in other industries and have been used to great effect in recent years by some oil companies, most notably Shell and Britoil. The point being made by Mr Burnett, re: garbage in, garbage out is axiomatic. However, in many applications the lack of hard data, on say reliability (mean time to failure), whilst unfortunate does not preclude meaningful simulation/analysis of subsea systems. This is especially true when it is required to identify a preferred scheme from several alternative systems or configurations in which similar key components are incorporated. The relative reliability, maintainability and hence availability can be satisfactorily determined; although it may be regarded as a desirable ultimate objective it is seldom necessary to arrive at precise values for these parameters.

It is precisely by using such techniques and applying a strict system engineered approach to subsea systems design that the impact of resource shortages, identified by Mr Burnett and Mr Barrett, can be reduced.

Regarding the way forward, Mr Burnett's points 1 and 3 relate to the type of R&D programs mentioned by him, and are outwith the scope of the paper. In the case of subsea separation/multiphase pumps (point 2), these could be utilised in conjunction with the types of subsea systems described in the paper. The maintenance philosophies and design rationale presented are equally relevant to production scenarios in which such facilities are incorporated.

P Metcalf (Fuel Subsea Engineering Ltd) Because every subsea production system is potentially different, each application must be engineered on a one-off basis even though individual components may be of a standard nature. This places a strong onus on engineers to systems engineer subsea production equipment in much the same way as practiced by other mature industries. This has been clearly highlighted in Stewart Adamson's paper.

Faced with the dilemma of a low capital cost and potential increases in operating cost, life cycle costing, which covers all aspects of design, construction, installation, operation and maintenance, becomes essential.

The role of the professional engineer is therefore to produce more cost-effective systems in the context of life cycle costs. In practice, this means a move away from sophisticated development schemes initiated in the late 1970s/early 1980s to much simpler yet still highly engineered schemes. In short, more technoeconomic solutions, without lowering engineering standards, will be required.

S M Adamson (Fuel Subsea Engineering Ltd) Mr Metcalf has succinctly confirmed my views on the design rationale for subsea production systems.

I thank him for raising the issue of life cycle costing. The multiplicity of variables involved in most subsea production systems, emphasise the need to apply the type of computer based simulation/analytical techniques presented in the paper as a design tool in support of broader systems engineering work. By such means, and by employing 'application engineers' (a type of engineer commonplace in most industries other than the oil industry), engineering standards can be improved in parallel with improvements in production availability from subsea production systems.