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

Introduction to Aspects of Economics and Logistics [and Discussion]

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Introduction to aspects of economics and logistics

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During the past five years the oil industry has moved its exploration and development programmes into progressively deeper waters, so that production operations in 150 m (500 feet) of water are becoming conventional, and exploration in water depths of over 300 m (1000 feet) commonplace.

The first part of this introductory paper is devoted to areas of opportunity in the deeper waters of the sedimentary basins of the world, with particular emphasis on the technical merits of these areas, and the size and high productivity necessary to justify their development. A description follows of the trend in licensing terms, the tax and financial arrangements that might apply, and the growing involvement of national oil companies and national energy policies with their consequent effect on the control of developments, right to export oil, and the division of profits.

The increasing importance of logistic and environmental factors on the technological requirements both in exploration and development is outlined, and some examples drawn of their political and sociological impacts. The development of supporting infrastructure in remote environments, of national preference for materials and services, codes of practice and further constraints in the overall capital investment programmes, are also outlined.

The final section deals with the economic implications of these international activities where during the course of the next 25 years it is expected that offshore oil production rates will double. The nature of the risk investments where exploration wells now cost between £3 and £5 M each, and capital costs for individual projects are over £1000 M, are examined, reflecting differences between the private sector objectives and national oil company objectives. Examples can be drawn from events in O.P.E.C. areas during the past five years.

Introduction

During the past five years the oil industry has moved its exploration and development programmes into progressively deeper waters. The extent of industry's interest may be gauged from the fact that all major companies have extensive deep-water licences some of which carry drilling obligations, as shown in figure 1. The gaps in the licensing pattern shown are partly due to unpromising geology but frequently due to licensing constraints or unfavourable licence terms.

An effective overall strategy for the exploration for and development of commercial hydrocarbons in deep water depends on a careful appraisal of the oil potential and technological and economic factors.

Geology

In the first place I intend to review in brief the critical geological and geochemical factors that determine the prospectivity of these regions – factors which are covered in more detail by Warman (1978, this symposium). The three principal factors are that

(*a*) the sediments must have generated hydrocarbons in sufficient quantity;

(*b*) there must be reservoir rocks of sufficient thickness, porosity and permeability; and

(*c*) structures must be large enough to justify exploitation.

Insufficient is known at present about the question of hydrocarbon generation in deep water. The governing factors must be essentially similar to those on the shelf. We require an adequate supply of organic carbon within the sediments, and this must be heated to a sufficiently high temperature, primarily through burial, to achieve the generation threshold. It is apparent that the type of kerogen, the insoluble organic matter, plays a large part in determining whether oil or gas is generated, humic kerogen of terrestrial origin being essentially gas prone, and the presence of organic carbon of marine origin being necessary for the generation of oil.

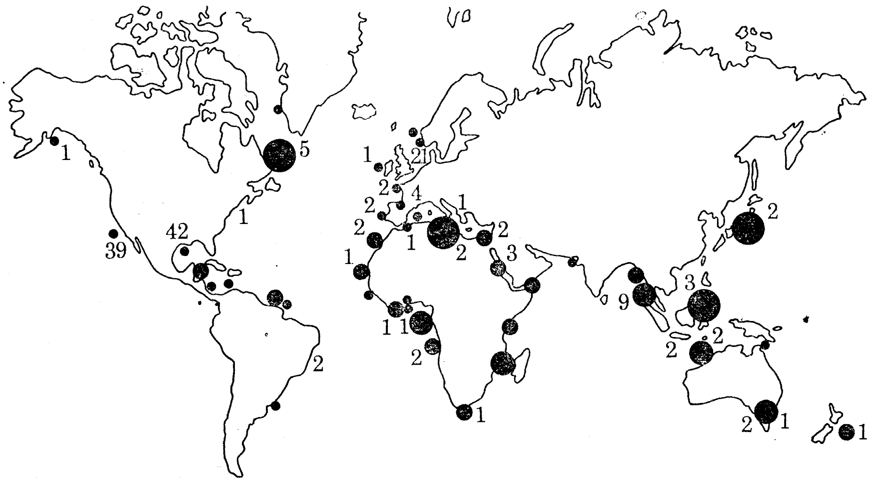

FIGURE 1. Deep-water activity at more than 200 m, April 1977. Before 1973, 36 wells were drilled, in 1973 the number was 5; in 1974, 10; in 1975, 33; in 1976, 58; in 1977 (to April), 17; total, 159. Circle size represents licence areas in thousands of square kilometres: the smallest less than 10, the next between 10 and 50, the next between 50 and 100, and the largest over 100.

Until recently it was therefore believed that there was a greater likelihood of oil rather than gas being generated from the essentially marine sediments found in the deep-water environment. Recent studies, however, have served to emphasize the importance of reducing or oxygen-deficient conditions for oil generation. Such conditions are far removed from the dynamic, well oxygenated, ocean waters that flow along the majority of present oceanic margins, but may be sought within basins of restricted circulation associated with the initial phases of ocean formation.

Consideration of average geothermal gradients and control from boreholes indicates that throughout much of the world a minimum sedimentary thickness of approximately 3 km is required to reach the hydrocarbon generation threshold of approximately 70 °C, although the most recent results from the Deep Sea Drilling Project suggests that this threshold may be attainable at a depth of as little as 1.5 km. Increasingly detailed information from the floors of the oceans confirms that the necessary thick sedimentary accumulations are present almost exclusively along the edges of the major land masses, from which they have been derived. The abyssal depths which comprise nearly 80% of the oceans have smaller thicknesses of sediment and are unlikely to yield commercial hydrocarbons (figure 2). With few exceptions our attention is thus concentrated upon the continental margins.

We must next consider possibilities for the occurrence of suitable reservoir rocks within this marginal sedimentary wedge or prism. It should be stressed that, with the exception of either fracturing or secondary porosity developed in chalks or other very fine grained lithified oozes,

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all reservoir rocks are ultimately of shallow-water origin, or are derived from a shallow-water source. Even the so-called deep-sea fan sands come initially from an erosional source either on land or in shallow water. Very few holes have been drilled to any depth on the continental slope. Some control in deeper water is available, however, from holes drilled by the Deep Sea Drilling Project. These confirm that the bulk of sediments present in the ocean basins and on

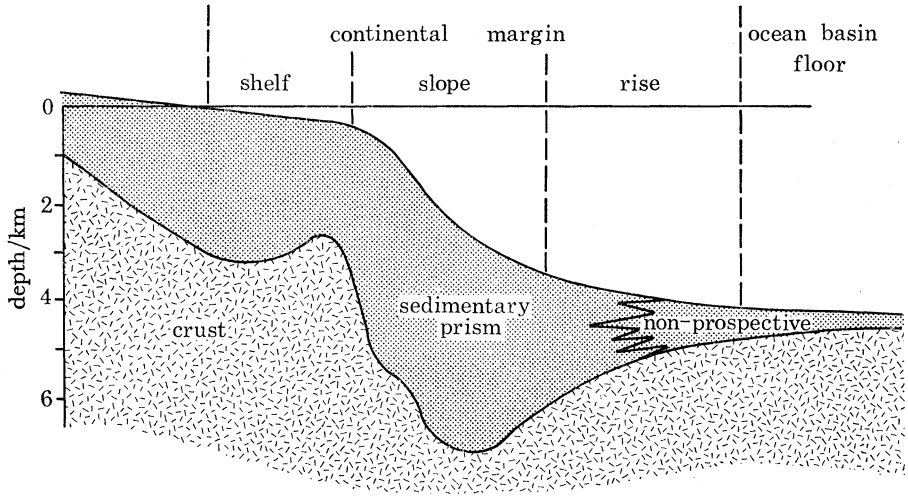

FIGURE 2. Schematic cross section through a passive continental margin.

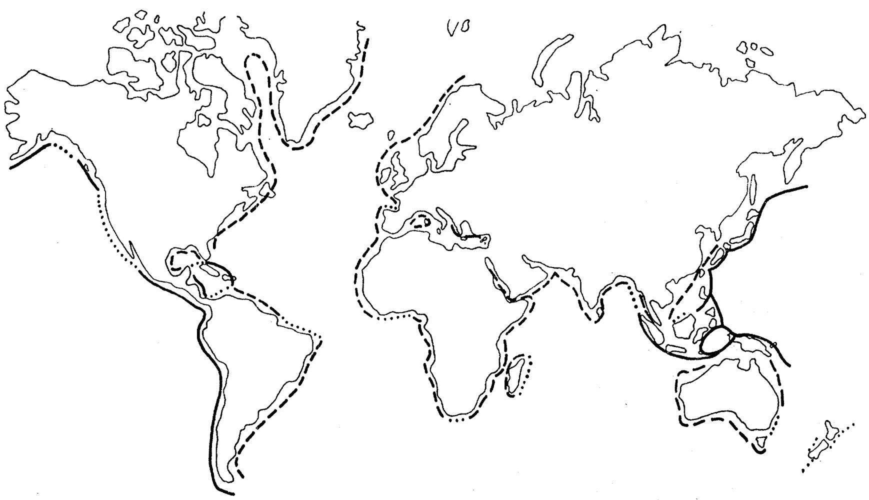

FIGURE 3. Continental margin types: ——, subduction; ·····, transform; – – –, pull apart.

the continental rises are fine-grained with low matrix permeability and are thus totally unsuitable as hydrocarbon reservoirs. Moving from the shelf into deeper water, we therefore expect an overall deterioration in reservoirs, both in quality and quantity. Whether this deterioration is gradual or abrupt will depend upon local circumstances. We have much to learn yet about the mechanisms whereby essentially shallow-water sediments, whether siliciclastics or carbonates, may be deposited in deeper water.

The other alternative is to seek reservoirs within the older rocks of continental margins that predate the formation of an ocean basin. These may include sediments of shallow-water origin subsequently depressed into deeper water as a result of continued marginal subsidence and/or

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sediment loading. Unfortunately, in many cases these prospects have been buried beneath later sedimentary accumulations at too great a depth for there to be much chance of extraction, if not of the existence, of commercial hydrocarbons.

The final factor to be considered in this geological résumé is that of structural deformation. Certain areas in the immediate vicinity of subducting margins typified by those encircling the Pacific show deformation of the marginal sedimentary succession. For this reason, coupled with problems of reservoir, these areas are not considered prospective. The prime exploration areas are therefore the passive or 'pull-apart' margins typical of much of the margins on the Atlantic, Indian subcontinent, Australasia, etc. (figure 3). By their very nature, passive margins are not the sites of compressional folding and over large areas seismic sections show the sedimentary wedge as undeformed.

However, structural deformation is present in a wide variety of areas and is of three principal types related to:

(i) basement features, typically horsts bounded by faults, for example the Exmouth Plateau of Australia;

(ii) salt or shale diapirs, associated with faults, for example in various areas off West Africa, such as Gabon;

(iii) gravity tectonics, including growth faults and simple folds as in the Gulf of Mexico.

Despite the presence of large areas of relatively undisturbed sediments on the continental slope and rise it is encouraging to note that large structures, often simple and domal, do exist and results of drilling on some of these prime targets over the next two to three years will be critical in sustaining any exploration interest in deep water.

Drilling

Exploration drilling has been extended into deeper water dramatically. By 1970 the record water depth for drilling had reached 456 m (figure 4), but since then the development of semi-submersible rigs and anchored drillships has made drilling to 600 m water depth commonplace and it is estimated that some 75 floating rigs can drill to 300 or more metres. However, the development of dynamically positioned drillships with computer based control systems, with buoyant marine risers and multiplexed electro-hydraulic blow-out preventer controls for great water depths, has extended the water depth record to 1055 m (3461 feet). At present some 8 rigs have a capability of drilling in 1000 m of water with some 6 rigs under construction, and of this total some units have a design capability of 1800 m water depth.

These deeper water rigs will give industry the capability of drilling efficiently and safely for commercial hydrocarbons over the upper continental slope.

Production

I should now like to refer to some of the problems related to the practical and environmental aspects of field development in deeper water. Initially it is perhaps appropriate to review the degree of multidisciplinary skills that are involved in one way or another within the overall development requirements (table 1). Fortunate is the company that has such wide and diverse skills entirely within 'in house' resources. The majority of smaller operators will require to use consultants as and when necessary and BP has recognized this potential in forming a Technical Services Group for the purpose of making such expertise available on a commercial basis.

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At present, offshore development by means of fixed platforms has been extended to 200 m for the North Sea and 300 m in the quieter water of the Gulf of Mexico. From studies undertaken by BP it is believed that at these depths of water we are at, or close to, the economic limit of such conventional platforms. It is, of course, relevant to add that the economic limit will be influenced by several factors, including the size and shape of the reservoir and also the well productivity. Additionally, the increasing momentum of subsea wellhead development

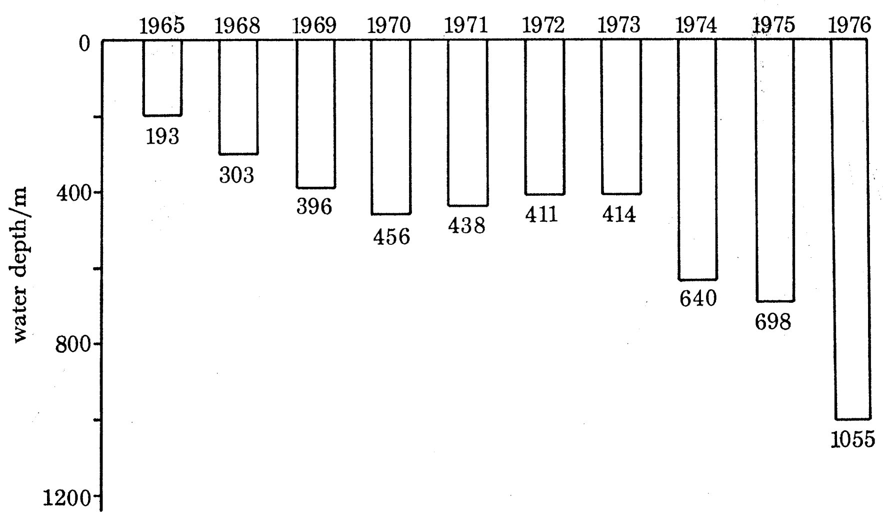

FIGURE 4. Annual deep-water drilling records (industrial operators).

TABLE 1. APPRAISAL FOR DEVELOPMENT PLANNING IS AN ACTIVITY INVOLVING MANY DISCIPLINES

the sciences	engineering	other
biochemistry	chemical	accountancy
botany	civil	cartography
chemistry	control	computer sciences
fluid mechanics	drilling	economics
geochemistry	electrical	environmental sciences
geology	electronic	ergonomics
geophysics	mechanical	finance
marine biology	metallurgical	law
mathematics	petroleum	management sciences
meteorology	production	medicine
oceanography	telecommunications	psychology
palaeontology		satellite navigation
palynology		social sciences
physics		surveying
statistics		

will tend to extend the application of conventional platforms and provide a springboard for deeper water technology. For the purposes of this review I propose to emphasize the trend and problems related to water depths greater than 200 m and for practical purposes limit the range to 650 m, which covers the new systems now under active development.

For the immediate future I would envisage offshore oilfield systems retaining facilities at the surface to house operational personnel and the major process and power facilities. Within this general concept considerable development work is under way in the field of tethered buoyant

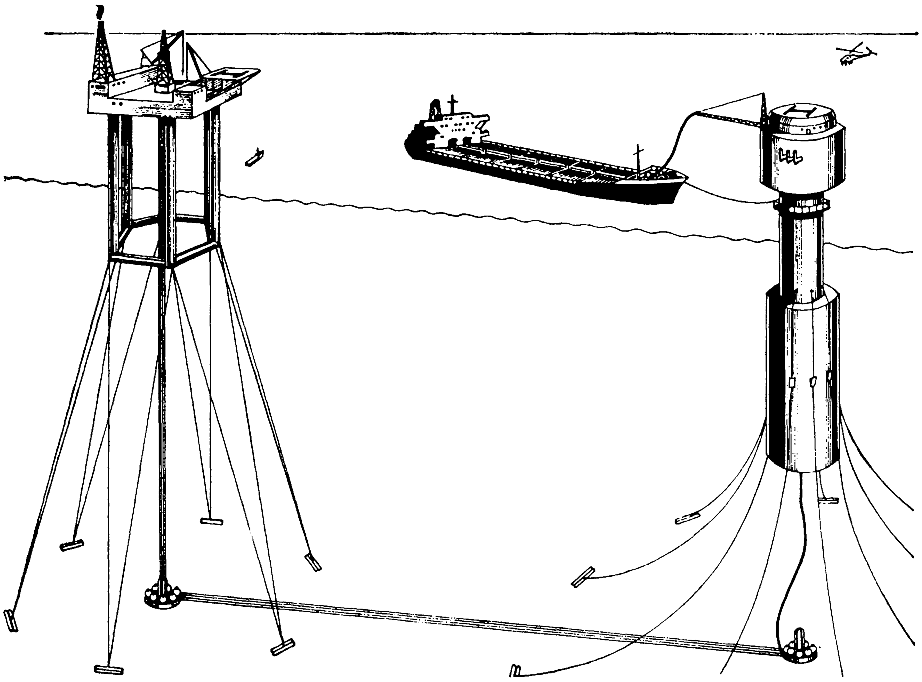

FIGURE 5

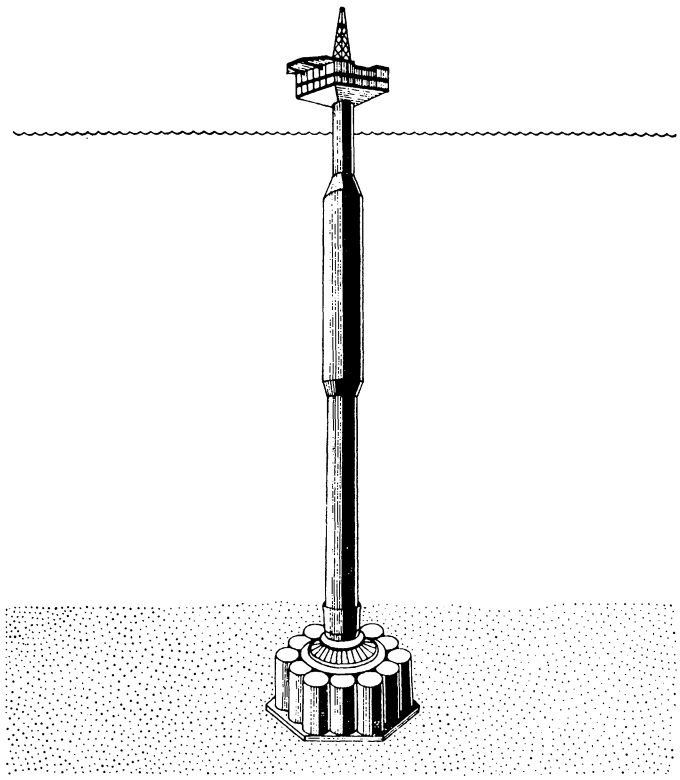

FIGURE 6. Arcolprod (Articulating Buoyant Column Production and Storage System).

platforms (t.b.ps) (figure 5), articulated columns (figure 6) and stayed tower (figure 7). All of these concepts are sensitive to payload and accordingly the development of efficient equipment for processing, power generation and effluent clean-up, requiring less space and of considerably reduced weight, will be of considerable importance to ultimate system economics.

Conventional systems so far installed have relied predominantly on the drilling of wells from a platform after placement at the field. This has necessitated concurrent drilling and production operations and reliable and safe procedures for accomplishing this have been developed. Notwithstanding the excellent record of the industry for undertaking such operations safely and efficiently, the Norwegian Petroleum Department have introduced (mid-1976) new regulations seeking to segregate these two operations which, if pursued, can only tend to have an adverse economic effect on the scope of conventional systems.

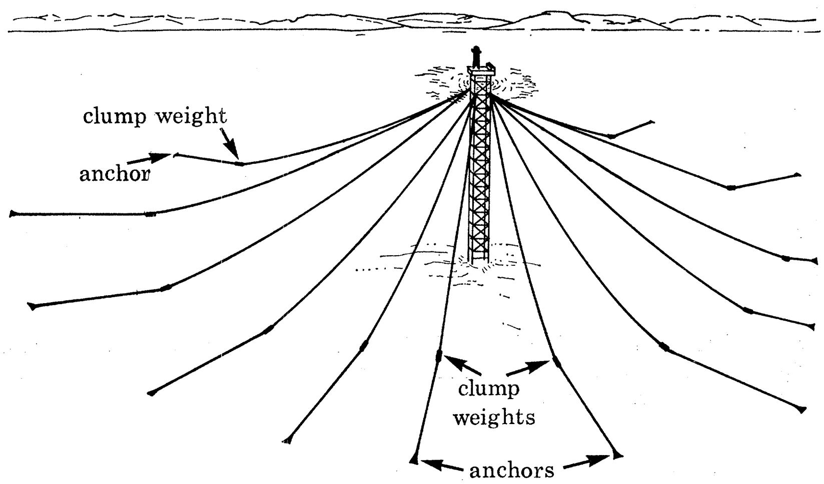

FIGURE 7. Schematic of Exxon stayed tower; deck area is 45 000 ft².

With such developments as tethered buoyant platforms there is opportunity to undertake drilling before installation of the platform, either directly below the platform, in which case the number of wells will by programme restraints be limited to 12–15, or alternatively at a number of well clusters located at strategic locations to allow efficient drainage and optimum deviation related to pay zone depth (figure 8). Well clusters of this form, say six wells per cluster, would have the advantage of limiting the number of producing wells to be closed in during workover (well maintenance) operations but would suffer the disadvantage of wells being remote from the platform for the more frequent service tasks normally undertaken by wireline on land or conventional platform wells. Pump-down tools, more frequently referred to as t.f.l. (through flow line) have been developed to undertake such work but the majority of current development and experience has been restricted to a tubing size of $2\frac{1}{2}$ in as applicable to lower productivity wells. For high producers such as are found in the North Sea, and will be required for viable deeper water developments, well completion requirements will necessitate 4 in, or perhaps larger, t.f.l. tools. Operation of such tools from a manifold chamber located at the well cluster will also require consideration as despite the added problems, the possible savings of potential well losses can be considerable. Figure 9 indicates the potential losses of production through twin 3 in and 4 in flowlines at various well flow rates at distances exceeding 3–4 km from the process facility. In total terms the back pressure on the well production system consists of losses in the well tubing, which is therefore greater for deviated wells and smaller tubing size; the length and size of flowline; and the lift to surface which relates to water depth. As this restraint increases with deeper water, consideration will need to be given to first-stage separation at the sea bed, which will also have the advantage of extending the range of flow without incurring surging, i.e. gas and oil separating out in the pipeline in the form of slugs which can cause considerable problems in the process system.

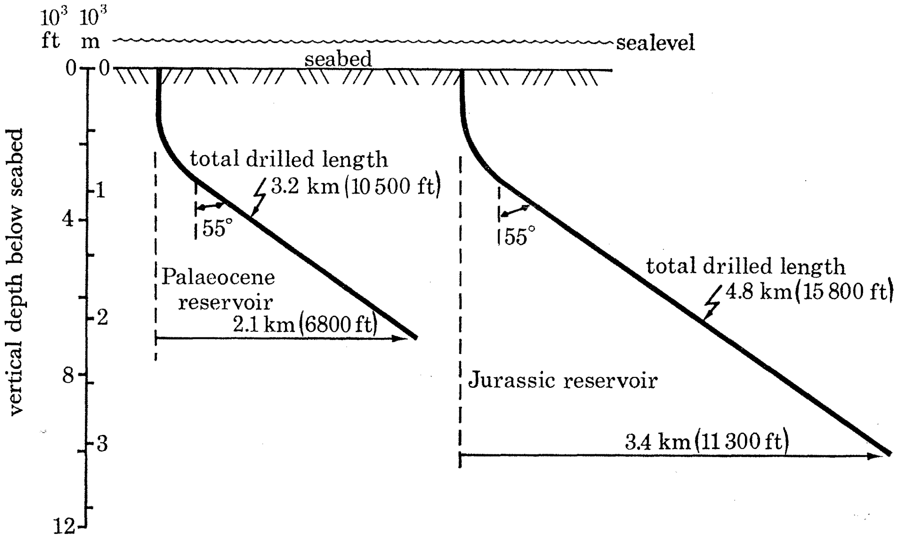

FIGURE 8. Reach radius of deviated wells. Well data: deviation commences at 1000 ft below seabed and the angle is built up at $2\frac{1}{2}°/100$ ft to a maximum of 55°. Areas covered: Palaeocene reservoir, 1360 ha (3360 acres); Jurassic reservoir, 3730 ha (9210 acres).

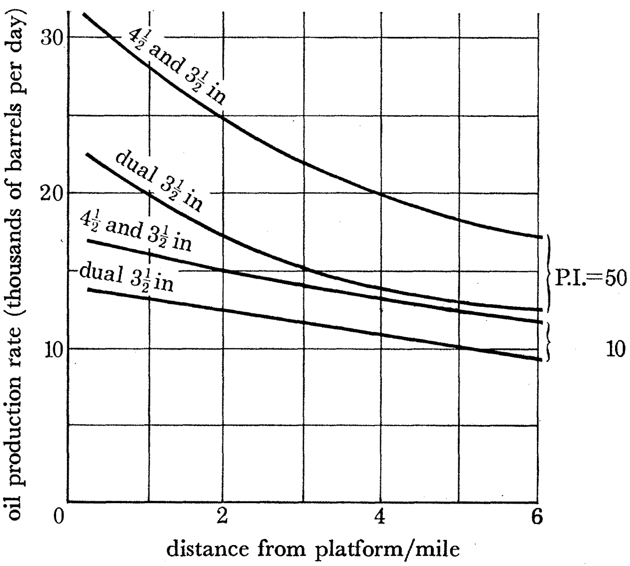

FIGURE 9. Typical North Sea oilfield peak production. $10\frac{3}{4}$ in casing: $4\frac{1}{2}$ and $3\frac{1}{2}$ in tubing and flowlines; $9\frac{5}{8}$ in casing: dual $3\frac{1}{2}$ in tubing and flowlines.

Of the systems currently under development it is reassuring to note that the basic operating techniques at the process facility are not too different from existing technology and hence the majority of experience gained in safety involving personnel and the environment will still apply. The same is not true of riser systems for oil and gas, which flex continuously with the horizontal excursion of t.b.ps, and considerable research and development is now in process towards resolving these problems. Also the range and scope of work that can be performed using subsea intervention systems is still the subject of active review, mainly related to the safety of personnel involved and safety of the environment rather than the basic concepts which have already been established in such systems as developed by Seal and Lockheed and under active development by Vickers Intertek. As we extend technology into deeper water it is inevitable that we will face greater problems related to the logistics of supply for both material and human resources necessary to operate and maintain the field installation.

Despite the considerable problems already faced and overcome in the North Sea and the Gulf of Mexico developments, their close proximity to fully developed industrial resources has been of major significance. In the case of the North Sea the industrial infrastructure existed before the event and the essential requirement was to build the necessary oil experience to it. Even this more limiting requirement has taken time to establish but it does help to illustrate the depth of problem that will exist when undertaking such development in the offshore areas of underdeveloped nations.

For such underdeveloped areas of the world, whose offshore area will considerably exceed that of developed areas, the development of a supporting infrastructure will need to feature in the very early development phases following identification of exploitable crude reserves. The oil industry has considerable experience from its past history related to earlier operations in the Middle East, but it is equally true that until fairly recent times the political and sociological impacts were of a much smaller degree than would apply today. Whereas in the past the tendency was for the operating company to develop its own infrastructure of industrial and social services within its field of operations and import the necessary materials and equipment, the requirements of today demand the maximum involvement of national resources together with the active participation of the host government. As the nature of offshore operations is to minimize the amount of work necessary at the offshore installation, e.g. maintenance as far as possible by unit replacement methods, it will be readily appreciated that the development of such an infrastructure may well incur more time and effort than the objective of developing an oilfield. Also to be included in such an infrastructure would be the vital service companies related to the supply of workover facilities, subsea intervention, and inspection services, and such companies would also need to be mindful of the aspirations of the host government, both with regard to the involvement of national investment opportunities and the training of nationals towards staffing such enterprises at all levels. As an example of these developments one need only review the changes that have taken place in such areas as Iran, Abu Dhabi, Qatar and Kuwait where in the course of the last two decades the rôle of the oil company has moved towards that of a service company rather than the earlier equity-based crude producer operating from within its own supporting infrastructure.

As the experience and confidence of national oil companies increases so will the tendency to introduce local codes of practice covering materials and services. Such a tendency could be dangerous and difficult to administrate if introduced in an indiscriminate and unprofessional manner and it is to be hoped that such will not occur. Certainly there is every reason to support codes of practice relevant to the geographical area of application and it is readily apparent that what is suitable for the placid waters of the Persian Gulf is not relevant to the North Sea, but, equally, divergence of regulations by different Governments for the same environmental conditions can only result in a degree of confusion. The objectives of the International Exploration and Production Forum formed in 1974 to represent the industry on an international basis will I hope successfully overcome any major problems in this respect by their close cooperation with governments and National Operating Committees.

Economic aspects of development

With increasing offshore development activity, and in particular as we move into deeper and more hostile environments, field development proposals must include more rigid economic appraisal in the early planning phases.

It will be readily appreciated that as recently as ten years ago the majority of oilfield development was still on land and the capital cost per barrel per day was of the order of hundreds of pounds whereas current offshore development is in thousands of pounds per barrel per day capacity. Additionally, risk factors related to the successful completion of offshore projects are correspondingly higher with regard to finance, programme time and environmental hazards.

Factors which have a bearing on development economics are shown in table 2.

Table 2. Factors affecting development economics

environment	water depth
	sea state
	seabed soil mechanics
reservoir	volume of recoverable reserves
	transmissibility
	shape
	pay depth
	thickness
	configuration
	crude quality
type of oil outlet	pipeline or marine terminal
timing of production	
licence terms	
crude pricing	

Water depth and environmental conditions determine the design requirements of the production platforms, with a move from gravity or piled bottom founded structures to guyed towers or tethered buoyant platforms related to economics. Not only are increased construction costs incurred in deeper water but installation times may be longer and the penalties of missing seasonal weather windows may be catastrophic.

The shape of the reservoir and the drilled depth, which affects well deviation, have a bearing on the reservoir volume that can be drained effectively from one platform: for a given volume of recoverable reserves a long narrow field with a thin reservoir section will require more platforms for effective drainage. Remote subsea well completions, tied into a central platform, will improve the drainage achieved by one production complex.

The volume of recoverable reserves and reservoir transmissibility are of paramount importance in determining the peak sustainable production rate and number of production wells required. Field development economics are sensitive to well numbers, particularly in deep water because of the high costs of deep capability rigs, and subsequent well maintenance.

Reservoir and crude-oil characteristics are important in determining process type requirement.

For land-based development there is no problem in extending the production facility as the knowledge of the reservoir increases, but for offshore development it is vital to include for all eventual requirements within the original project if the most economic development is to result. Within the information available from appraisal drilling the prediction of all reservoir characteristics and future behaviour is no easy task.

Naturally all these factors must be taken into account when planning a field development and extensive sensitivity testing must be applied to determine those factors that have most impact on the overall economics, in order that the programme and development planning can be tailored to minimize the effect of the key variables.

To illustrate this point, economic evaluation often demonstrates very forcibly the advantages of planning development to give production at the earliest possible date following financial commitment. Such a situation is difficult to achieve from platform drilling as there are definite limitations both technically and logistically to the number of rigs that can operate from a platform. Subsea completions will in the near future provide the most effective solution to the early production requirement, albeit that the maintenance of such subsea completions will be technically more difficult and more costly than conventional platform wells.

Having said all this, it is apparent that each field discovery will be subject to its own set of development conditions and it is not practicable to make really significant generalizations which relate water depth to economic reserve size. Nevertheless, one can very broadly say that under many existing tax régimes, and assuming crude prices remain constant in terms of purchasing power, then large recoverable reserves (of at least 5×10^9 barrels, i.e. giant field) allied to high and sustainable individual well flow rates (5000 barrels per day or better) appear necessary if fields in around 500 m water depth will be economically viable.

This economic assessment has feedback to the exploration geology outlined earlier. It is evident that the very factors which are desirable in deep water, namely good transmissibility and large reserve size, will be elusive. Fields of the required size will be restricted in number (giant fields are estimated to represent less than 1 % of the world's fields but account for 75 % of global reserves), and therefore any method of production, such as subsea well completions, and any improvement in licence terms such as those discussed in the next section, will encourage the search for smaller fields and their exploitation.

Licence terms

I have identified the factors affecting the size of field, the productivity necessary to justify development in deeper waters, the engineering and environmental aspects, but not least among these are licensing, tax and other financial terms. In the face of the growing economic and political significance of oil there has been a general tightening of terms in recent years on a world-wide basis. The results of this are increased government take, direct or indirect control of activities and state participation but only rarely with State involvement in exploration risk.

Terms vary enormously but for the most part fall into three broad categories:

(1) Royalty/tax terms as we have in the U.K. and Norwegian sectors of the North Sea. Under these terms, government take could be some 75 % or more.

(2) Production-sharing terms such as apply in Indonesia and Malaysia, generally with production split after cost recovery, in the range 70:30 to 85:15 in favour of the State.

(3) Service contracts.

State participation without involvement in exploration risk, superimposed on these terms, is a further burden. Participation can be as high as 75 % in certain circumstances.

Any state requirement to defer development of discoveries, restrict production or statutory variations of terms during the life of a project can have severe effects on the economics as far as the companies are concerned and can undermine confidence in continued exploration.

At present, terms rarely differentiate between developments in shallow and deep water although in some cases discretionary provisions exist to reduce royalty and/or tax to encourage development of marginal fields.

However, increasing activity in deeper water with the much higher exploration and development costs and considerably greater risk justifies special consideration. Perhaps what are required under either royalty/tax or production-sharing terms to provide the necessary incentives for exploration and development are:

(1) Bonus bidding should be replaced by committed exploration programmes, so that maximum investment is made in exploration, but there should be more discretion about such commitments and onerous requirements should be avoided.

(2) Depreciation rates and other financial provisions should be such that costs are recovered over as short a period as possible in order that the companies can recycle cash into further exploration and development.

(3) The terms should be flexible to ensure that the economic cut-off for field development is as low as is realistically possible and such flexibility should be statutory and not discretionary.

(4) Reasonable assurance is needed that terms will be stable during the life of a project and not subject to arbitrary change after investment decisions have been taken.

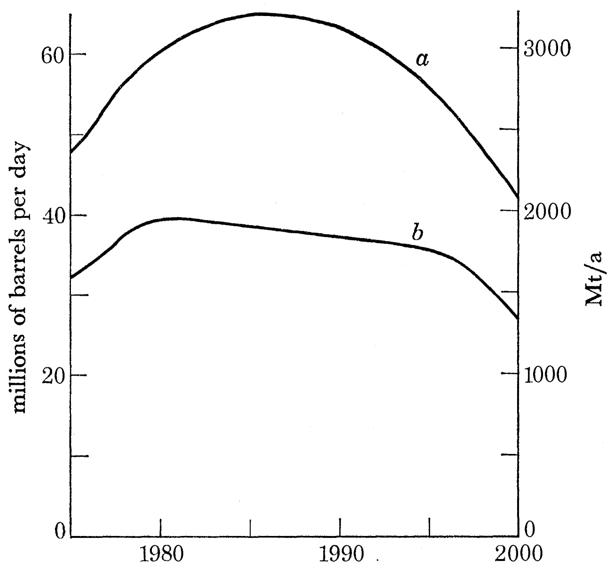

Figure 10. Non-Communist world crude oil availability. (*a*) Total crude production; (*b*) O.P.E.C. production range at full production capacity.

The international scene

Energy forecasters in the oil industry, government agencies, and academic institutes are unanimous that the world will need additional oil supplies, at least for the next decade. Equally, they predict a large increase in the use of gas as new supplies are developed and moved internationally. However, there is now wide acknowledgement that world oil production is likely to reach a peak some time in the 1980s, the precise timing depending on the policies of the governments of the major oil producing countries – including the United Kingdom and Norway as well as Saudi Arabia and Kuwait – and also of course on new discoveries. However rapidly alternative energy sources such as coal, nuclear, hydro and solar are developed, because of the technical lead time and the practicality of projects, major new supplies from these sources will not be available to meet increased energy demand for at least ten years.

Figure 10 gives an illustration of the crude-oil availability to the non-Communist world and the part that the Organization of Petroleum Exporting Countries (O.P.E.C.) may play, assuming that new oil reserves to be discovered and developed in the period will provide about one-third of the production potential in the year 2000, and O.P.E.C. oil prices as the price setter will be at least maintained in real terms. Peak availability in the second half of the 1980s emphasizes the need for intensive oil exploration programmes.

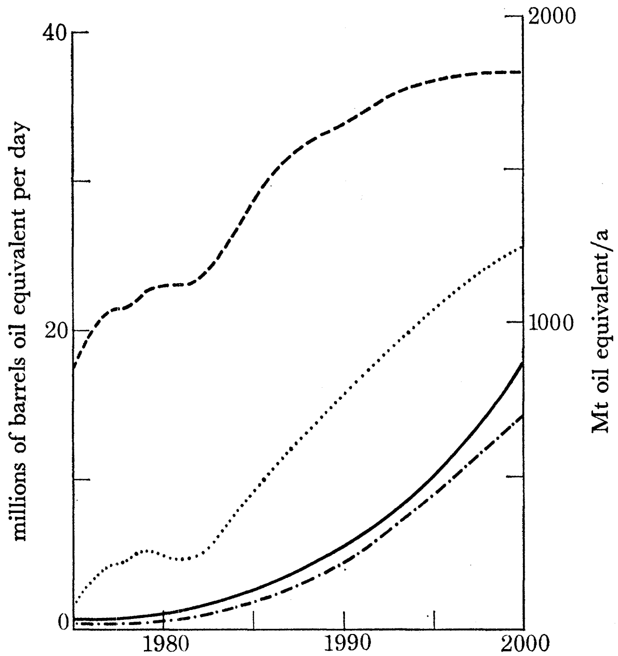

FIGURE 11. Non-Communist world natural gas potential, production and trade: ---, Non-Communist world production potential; ·····, O.P.E.C. production potential; ——, total international gas trade; liquefied natural gas trade.

Figure 11 illustrates an even more dramatic development of gas reserves, where it is assumed that new gas discoveries will provide well over half the production potential in the year 2000. Apart from the indication of a tremendous rate of growth of the international liquefied natural gas trade (the majority from O.P.E.C. areas), in energy terms there may be as much gas required as oil to meet the free world requirements by the year 2000.

For the Communist world, including China, as indicated by a recent Central Intelligence Agency report, and on our appreciation, oil production potential may peak well before 1990 at about 15×10^6 barrels per day, sharing common problems with the free world.

The prospects offshore within this overall scenario, however, are the most promising with production potential from new discoveries forecast to be at least equal to the current potential of about 10^7 barrels per day.

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It is not surprising that offshore exploration and production investments have more than doubled in real terms in the past three years, and are expected to increase in the foreseeable future. In BP's own case, 80 % of its exploration investment is offshore in mainly non-O.P.E.C. areas, and its exploration and production investments for oil, gas, coal and minerals account for a half or more of its total investments in the next 5 years.

The rapid increases in unit development costs offshore are alarming, and pose problems for the future. Exploration wells are already costing up to £5 M each, and individual projects over £1000 M. As smaller structures in deeper waters are developed, costs may treble in real terms over the next 10 years. The biggest projects may be in the £10 000 M range. Such investment levels, which may be estimated in the order of £200 000 M in the next ten years world-wide, are only within the capability and scope of international oil companies with the technology, management and asset base to support such activities. The consequences of such investments cannot yet be gauged, although it is likely that long-term rates of economic growth may be constrained by an altogether higher energy-cost plateau.

Since at least half of the offshore prospects may reside in O.P.E.C. countries and less developed countries (l.d.cs), this is of particular significance. First, during the past decade the position and importance of state oil companies within these areas has become increasingly predominant. Consequently western oil companies now often find themselves restricted to supplying management and technical services on a risk basis; that is, supplying the capital for exploration and development to be recouped only in the event of success, and frequently with rigid limits on the rates of return which may be expected. The temptation to move into barter deals, where imported goods and services are paid for by oil and gas supplies, produces further complications since such arrangements may involve both government-to-government and inter-governmental department negotiations. Secondly, there is a marked reluctance by private investors to embark on projects in some Third World countries because of the risk of political expropriation of their assets without adequate recompense. This is a particular hazard in the case of energy development projects and it is here that the question is raised whether there can be developed some form of guarantee, for example in conjunction with the World Bank as recently suggested by President Carter, that will ensure that the much needed investment to develop the potential offshore reserves of l.d.cs will not only be forthcoming but will be adequately protected.

Dominant is the rôle of the U.S.A., which in 1976 consumed 35 % of the free world's supply of oil with only 8 % of the proven reserve, and also consumes 62 % of the free-world gas sales while having no more than 15 % of the proven gas reserves. The rapidly growing dependence on imported oil on the one hand and, on the other, the need to conserve, economize and develop alternative energy sources will dominate energy policies as reflected by President Carter's recent statements.

The pattern of availability of U.K. offshore oil and gas supplies is markedly similar to the pattern of supplies for the free world, if our forecasts for new discoveries in the U.K. sector of the North Sea are correct. The experience gained should be directed with confidence to the world-wide opportunities, where there is a foreseeable need to increase the non-Communist world's oil production from some 50 to 65 or 70×10^6 barrels per day in the next 10 years, a large proportion of which increase should come from non-O.P.E.C. areas, and significantly from offshore areas. This (together with ambitious programmes for other types of energy) is a challenge to all in the industry if economic growth in the western world in the next quarter of a century is to be kept in the range of 2–3 % per annum.

Discussion

G. L. Hargreaves (*Petroleum Engineering Division, Department of Energy, Thames House South, Millbank, London SW1P 4QJ*). Dr Birks has mentioned the very severe environmental loads to which fixed production platforms are exposed and further stated that such structures are very sensitive to deck loads, which must therefore be kept to a minimum.

Has Dr Birks considered the possibility of placing only a terminal structure above the sea's surface, connected by a shaft, or shafts, to production facilities housed deep down on the seabed, all but immune to wind and weather and where weight would be a stabilizing factor rather than a disadvantage. How would such an installation affect the economic viability of marginal deep-water oilfields?

J. Birks. I should like to consider Mr Hargreaves' question in the context of transferring the major production facilities to the seabed rather than the means by which this might be achieved. If we consider only the gas-separation process then the problems posed are by no means insurmountable provided the system can ultimately be tied back to the surface. Such a subsea separation system was in fact installed offshore Abu Dhabi in 1970 and commissioned in 1971 for a joint BP/C.F.P. development programme. Although at that time problems were experienced in the control and electrical systems, technology has subsequently been developed where such a system can be considered to be entirely feasible. However, when we consider the total production system requirements for a field development we must also cater for water process/injection, gas process/injection and power generation, etc. These requirements result in a very significant power load, normally at least 30 MW, and if these are enclosed in a seabed chamber or shaft the problem of maintaining a safe environment would be formidable. Earlier experience by BP with unmanned production facilities has not been very encouraging, both from a safety and efficiency point of view, and therefore the problem of operating personnel at the seabed would also have to be contended with. While we in BP have considered such concepts superficially to identify problem areas we cannot claim to have studied them in great detail for the reason that the present developments referred to in my paper appear to us to be more viable and practical solutions for water depths of up to 650 m.

I should perhaps also stress that the benefits of weight reduction are not entirely related to the technical feasibility of the systems but more importantly to extend the viability of such developments. I would suggest that when serious development is applied to total subsea production systems the volume/space requirements for such equipment will be of equal importance to the viability of such concepts. With regard to Mr Hargreaves' final question related to the effect of such total subsea systems on marginal field developments I can only reply that it is my present view that they would be less favourable than the concepts to which I have referred in my paper.

E. G. West (49 *Oxford Road, Stone, Nr Aylesbury, Bucks. HP*17 8*PD*). The excellent review by Dr Birks demonstrates very clearly the interrelation between the many technical and economic factors which tend to increase by an order of magnitude as the greater depths of the water are explored and exploited. Of the many comments and questions which come to mind, I will mention only two. The economic factors are inevitably influenced by political questions and an area of special importance is the possibility of enhancing the recovery of oil, which involves some quite complex scientific and technological problems. I feel sure that we should all appreciate information on any measures which could be used, or on which further research should be undertaken, to improve the yield from existing fields which, we understand, is considerably below 50 %, and averages only 35 %. Admittedly the cost of enhancement measures is high and it may well be that conventional means are uneconomic today but as shortages develop and fuel prices rise or as political–economic factors change, it is likely that the cost of additional recovery would be worth while. Oil left in the reservoirs now might not be recoverable after a lapse of time and this suggests that means to increase the yield should be in operation without delay, otherwise more than half the oil in the existing fields will be lost while we are recovering oil from newer wells in deeper waters at still higher cost. Hence, further research into enhancement should be undertaken sooner rather than later and the full economic factors need to be set out. Are there plans in hand for work on the necessary scale? Surely it should be on an international basis as a major contribution to the world energy problem.

An entirely different topic arises from my interest in structures. It was noteworthy that there is the need to reduce the weight of the superstructures, accommodation modules, etc., and this suggests that attention should be turned to the structural use of aluminium alloys for such items. Taking full account of the different physical and mechanical properties of aluminium alloys and steel, there can be overall weight savings of 50 %. The value of such weight saving can be set against the additional cost of aluminium over that of steel. The cost of fabricating need not be different and aluminium alloys for marine conditions can be readily welded. There would be further advantages in reduced handling and transportation costs of complete structures and of structural elements. In addition there are substantial longer-term savings due to the better corrosion resistance of aluminium compared with steel, leading to less frequent and lower expenditure on maintenance.

J. Birks. In reply to Dr West's comments, I would first emphasize that oil companies have for many years been seeking to improve the percentage of oil recovered and have carried out extensive research to this end. The relative lack of success, except for the now well-established technique of water injection, is itself an indication of the technical difficulties involved. While it is possible to achieve 100 % recovery on a rock sample in the laboratory by chemical methods, any improvement on a field scale is a much more complex problem with each field presenting its own combination of difficulties.

While there is some technical debate at present on the relative merits of early and late application of enhanced recovery techniques, there is of course a strong economic incentive to achieve any improved recovery during the normal life of the field facilities, particularly offshore. On the other hand, it would be unrealistic in present circumstances to consider delaying development of new fields in the hope that better techniques will become available quickly. None of the currently available techniques appears to be economic.

BP recently hosted a symposium on enhanced oil recovery, by which the experiences of major Oil Companies and Research Institutes in this field could be exchanged. The majority of the field trials on enhanced recovery were conducted in the United States and invariably the nature and homogeneity of the oil-bearing intervals resulted in inconclusive results on the effects of additives on water floods. Another practical problem is the high degree of absorption of such chemical additives by the formation rocks themselves, resulting in rapid dilution of the active agent at the water/oil interfaces. Emphasis was directed in this symposium to sea-water injection operations, which are likely to be the predominant recovery processes in the North Sea oilfields.

In this the most significant and economic impact of additives could be the improvement of injectivity rather than significant improvement in oil displacement efficiency. BP are planning to initiate field trials in the Forties field of such additives later this year.

The consideration of future oil shortages has led various governments to support more research in this area. In the U.S.A. a major programme is being supported by the Energy Research and Development Authority to the extent of $60 M p.a.; in Europe the E.E.C. is already supporting research in its member countries apart from that supported by the national governments. In practice, the results of this work become generally available through publications and conferences so that the effort may be regarded as a truly international one. As the research moves more from the laboratory to the field experiment stage, the costs and the technical uncertainties will rise steeply and the scale of the support may have to rise correspondingly.

The possibility of reducing platform superstructure weight by replacing steel with alternative lighter materials has been an active interest for a number of years, but the progress made in actually using such materials has so far been rather limited. The various materials that might be used all have some disadvantage, and in the case of aluminium alloys the main problems have been sparking hazard, loss of strength in the event of fire, and the difficulty of ensuring satisfactory standards of workmanship in using a relatively unfamiliar material. The main present use of aluminium alloy is probably in the fabrication of accommodation units. There will undoubtedly be an increasing use of this and other alternatives to steel, but the overall room for reducing the weight of platform superstructures by this means seems likely to be rather marginal.

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