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Modern Petroleum Technology

Volume 2 **DOWNSTREAM**

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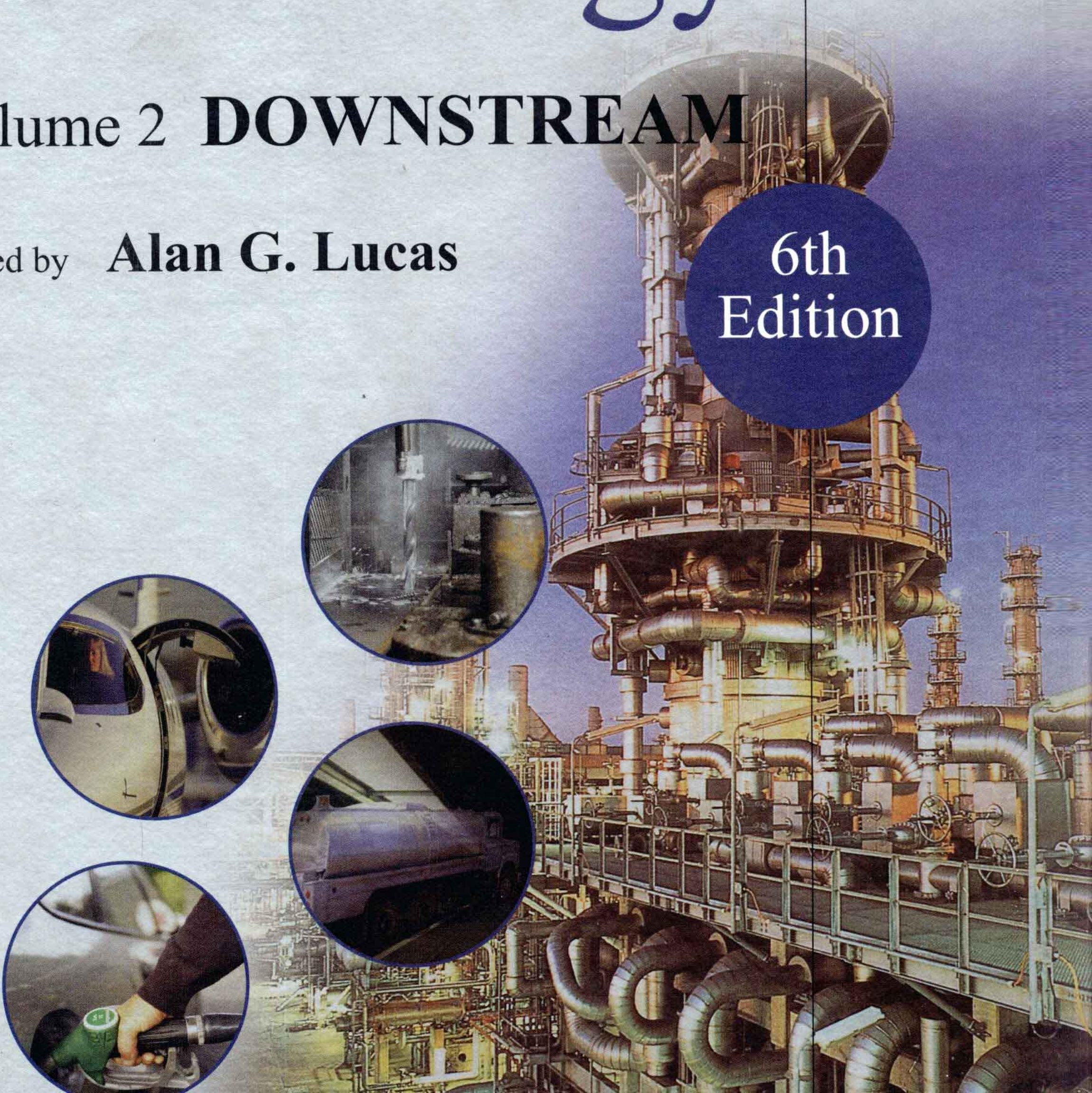
6th Edition



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Modern Petroleum Technology

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Volume Editor's Foreword

The purpose of this volume of *Modern Petroleum Technology* is to provide an accessible and authoritative account of the core technology of the international petroleum industry in the fields of oil processing and oil products. Its authority comes from that of its contributing authors—drawn from major integrated oil companies, from more specialised companies, from leading technology companies and technical institutions—all with outstanding reputations for technological expertise in the areas to which they have contributed chapters.

Downstream oil technology is increasingly global in nature, and this volume seeks to be global in its perspective. Authors drawn from Finland, France, Germany, Japan, The Netherlands, the United Kingdom and the USA have helped greatly in achieving this objective.

The two major factors which have driven petroleum technology development in recent years have been identified by Peter Ellis Jones in his overall introduction to this new edition of *Modern Petroleum Technology*, as economic pressure and environmental concern. These factors impinge directly on the activities of the downstream industry, most clearly in the field of oil processing. In oil products, the major impact is felt via the customer, both the direct customer who buys the product and the 'intermediary' customer: the vehicle or equipment builder (often called the OEM—the Original Equipment Manufacturer), whose product provides the end use. The oil industry works closely with these OEM industries, usually attempting to anticipate their requirements. The numerous references to OEMs in the product chapters illustrate the importance of this cooperative approach.

Technological development in downstream oil is usually evolutionary rather than revolutionary; lead times can be long, its introduction gradual, and change and progress do not occur at the same speed in all parts of the world. This can lead one to underestimate the cumulative impact of technological development over time—which is huge. Take, for example, the motor car. For a middle-aged driver, words like 'rebore' and 'de-coke' exist only in memories of childhood; fuel consumption has halved, oil change periods have trebled, and exhaust emissions have been reduced to a fraction of the levels when he or she first drove a car. The technology which has enabled all of this is described in the following chapters.

All who benefit from this book owe a debt to its authors. They have given generously of their time and expertise and, as editor, I thank them all. In particular, I wish to record the contribution of Alan Bridge, who wrote his chapter on Hydrogen Processes when already seriously ill and who died very shortly after its completion.

Introduction

P. Ellis Jones

This completely new edition of *Modern Petroleum Technology* presents the best technology used in the international oil and gas industries today, as described by an eminent group of authors drawn both from leading oil and contracting companies and from prominent academics in this field.

This edition follows some 16 years after the previous edition, which remains widely used in many areas of the world and is still regarded as an authoritative source on oil and gas technology. This may seem surprising but, if we compare the oil industry with such industries as microelectronics or pharmaceuticals, we see a very different pace and character of technological change; this is reflected, no doubt, in the fact that microelectronic and pharmaceutical companies typically spend between 12% and 20% of sales revenue on research and technological development compared with less than 1% to 3% of sales revenue in most oil and gas companies.

1 THE CHARACTERISTICS OF MODERN PETROLEUM TECHNOLOGY

Technology in the oil industry tends to be evolutionary rather than revolutionary. Rarely does a researcher in the oil industry come up with an entirely new product or a process which will open up a completely new market application for oil products or which will give us an entirely new route to the production of a product. Most research and development is orientated towards evolutionary improvement—How can we achieve better yields from an existing process, how can we improve the quality of exploration data, or how can we produce our products to new quality standards that meet the ever higher expectations of regulators and customers?

Technological development in the oil and gas industries also derives predominantly from applied technology rather than pure 'blue sky' science. If we look at the very real advances which have taken place over the past 15 years in geophysics or in process control, to take two important examples, these have principally been facilitated by major breakthroughs in microelectronics and in computer science, which the oil industry has been skilful and successful in appreciating and applying to its own requirements.

If we look at the major technological developments in offshore engineering, the story is the same; the materials scientists and the computing specialists have developed stronger, lighter materials and more advanced CAD and structural analysis tools

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respectively, which the oil industry has successfully applied to the design of safer, cheaper and more reliable structures as its operations move into deeper waters.

The technology of the oil industry tends to be very international. To a great extent, it is the same oil companies and the same international service companies which are found in most areas of the world and, not surprisingly, the technology that they employ is broadly the same in whichever country they operate.

Oil companies tend to rely much more heavily than 20 years ago on the use of specialist contractors and service companies throughout their operations. This has two important effects. First, it permits the service companies to spread the cost of developing technology across their operations on behalf of several oil companies. Second, it has made it possible for an oil company which does not have either the wish or the resources to develop its own proprietary technology base to access the latest technology through the careful selection of contractors or consultants with that capability.

An effect of this is that, unlike in some other industries, access to technology is rarely a decisive competitive factor in the oil industry today; nor is it a barrier to entry for potential new entrants to the industry. The latest technology is readily available, although frequently at some significant cost. It is, of course, true that there are certain areas of process technology, for example, where some of the major oil companies have proprietary technology, the intellectual property over which they have legal protection, but in most of these cases that technology is regarded as a profit centre and can be licensed where appropriate even by competitor companies. The major international companies cannot therefore be regarded today as being 'custodians' of the industry's technology in the way in which many of them would have seen themselves 20 years ago. To an increasing extent, technology has become a commodity.

What then really drives the technological development of the oil industry, an industry whose operational ethos tends to be risk-averse and frequently conservative in applying new technology? The answer lies in three words—*economics, safety* and *environment*—the three principal preoccupations of oil industry management at the end of the twentieth century.

2 THE ECONOMIC INFLUENCES

Fierce economic competition has been one of the key characteristics of the international oil industry since its earliest days, and this characteristic has been strengthened over the past 20 years by the global trends towards deregulation, competition and privatization, creating a more pluralist industry that consists of many more 'players' in each segment of the industry and more transparent transfer prices between them.

In the two decades before the first oil price shock of 1972, economic growth in the industrialized countries was largely predicated on the availability of cheap oil, principally from the countries of the Middle East. This led to a steady growth of demand, averaging about 7% per annum throughout that period, representing a doubling in oil demand every 10 years or so. The implications of this growth rate on the technology of the oil industry were clear. The priority was to capture the economies of scale, exemplified by the fact that over this period the size of the largest ocean-going tankers increased from 50 000 d.w.t. to in excess of 300 000 d.w.t. These economies of scale permitted the oil companies to contain or even reduce their unit operating costs per barrel of oil despite manning levels which would be regarded as highly extravagant by today's standards.

Such an era was very forgiving of the errors of corporate planners. If we overestimated demand in the market it probably had no worse consequence than that our company had brought on stream new capacity one or two years early. Since construction costs were escalating year by year, such premature investment carried little real economic penalty and could even be portrayed as prudent pre-investment to meet the growing demand. During that period the large oil companies, with their preferential access to cheap Middle East crude and integrated systems, were generating very healthy cash flows, out of which they were able to finance the considerable investment in new operating assets necessary to meet the growing demands with little recourse to outside equity or debt markets. Since much of the profit was generated from access to and the uplifting of crude oil. The objective of refining and of marketing investment was principally to enable the company to run the maximum amount of crude through its integrated system; this best served the integrated economies of the group as a whole.

These economic verities applied most strongly in the case of BP and Gulf, traditionally 'long' on crude oil production, and least strongly in the case of Shell and Mobil, companies traditionally 'short' of crude (that is, net purchasers) for whom the concepts of adding value to their crude through the production of higher value products such as petrochemicals and lubricants and through investment in markets were more important even in the early 1960s.

All of these comfortable economics changed for ever in 1972/3 in the wake of the first oil price shock; the price of crude oil was raised around four-fold from around $3.00 to over $12.00 per barrel; the major companies lost much of their preferential access to OPEC—and particularly Middle East—oil, which had been both a principal source of profit and the key to their ability to control the industry through integrated systems; and, finally, there was a very real public perception for the first time that oil was a scarce and finite commodity.

The response of the major companies to the challenge of this first oil price shock conditioned the technological priorities of the oil industry for the next 15 years. For example, the major companies had lost their 'equity' crude reserves in the Middle East and thus sought new sources of equity crude through exploration and production in many of those countries that were becoming accessible to them for exploration for the first time. Many of the most prospective exploration plays were offshore or in hostile environments to which the industry would not have been attracted at $3.00 per barrel, but which had considerable allure at $12 per barrel with the prospect of further increases over the life of the field.

The technology of offshore exploration and production was already developing before 1972, but the changed priorities of the industry after that year gave huge impetus to the development of offshore technology, particularly in the hostile conditions encountered in the Northern sector of the UK and Norwegian North Sea. It is remarkable that within a very few years from first discoveries in the East Shetlands Basin and Central Graben we had on stream the Forties and Brent systems, for which much of the technology had to be developed or adapted while these massive projects were still under development. The major priority of the technology was to find safe and reliable solutions to the engineering problems of bringing on stream these large fields and of economically conveying their oil to shore, a distance of some 150 miles through the waters of the Continental Shelf.

By the mid-1980s the fear of oil shortage and perceptions of the level of future oil prices had both moderated. Oil price weakness began to affect the industry's cash flow in 1986 and this caused a number of major offshore development proposals to be reconsidered. In areas such as the UK North Sea, there was a prevalent view that the large 'easy' fields had mostly been found and that the new discoveries, which continued to be found with remarkable regularity, would principally be of smaller size, greater geological complexity and in many cases in deeper water or more hostile environments.

Management attention and technological resources were therefore directed to new development solutions. In the North Sea we saw the first tension leg platform (TLP) and in the Gulf of Mexico a number of variants of the compliant tower concept, both innovative and cost-effective solutions to the development of medium/large oilfields in water depths where the concrete gravity structures (Condeeps) and large steel jackets that had been the mainstay of development throughout the 1970s and early 1980s would have been disproportionately expensive to develop and might not have proved economic on the new oil price outlook.

The great advances made in geophysical technology in the early and mid-1980s have been particularly significant in enabling the industry to adjust to a lower crude oil price and to look with some equanimity at the prospect of developing new offshore oilfields against a $18 per barrel price scenario. The rapid development and adoption of 3-D seismic for offshore geophysical surveys was clearly the most important of these advances, but other advances in marine data acquisition and on-site quality control, the availability of greater computer power for processing the very large data sets now available and the widespread availability of digital workstations and automated cartographic drafting all contributed to a complete transformation in the quality and cost-effectiveness of geophysical output, and in the productivity of geophysicists and their support staff.

These developments in geophysics and parallel developments in petroleum engineering, where greater computing power facilitated the routine use of much more powerful reservoir simulation and modelling techniques, enabled companies to plan their offshore development on the basis of many fewer appraisal wells than would have been considered prudent only a few years before. As many of the new discoveries being made were relatively small compared with the large fields of the early 1970s, this greatly improved their commercial viability. Not only was the cost of drilling expendable appraisal wells reduced or eliminated, but the time lag between the first discovery and first production was potentially reduced by many months, a surprisingly sensitive element in the economics of a marginal field.

In the downstream oil industry, and in particular in the refining sector, the reaction to the higher oil price after 1973 was very different, but this also shaped the industry's technological agenda for the next 15 years. The higher oil price after the shocks of 1973 and 1979 reduced or at times even eliminated growth in market demand for petroleum products. Refinery expansion plans were consequently curtailed and plans for 'green field' refineries abandoned, particularly in Europe and North America. The major oil companies had lost their access to Middle East preferential crude oil and were effectively forced to purchase their crude at transparent open market prices, offering them no significant advantage over competitors who had not previously had access to cheap Middle East equity oil.

No longer were refineries links in an integrated chain, where the ability to uplift and run additional volumes of crude oil through the system was the principal economic imperative. The key to refinery economics became the addition of value—the excess of realizable value of the saleable products over the cost of crude and other feedstocks, and other economic inputs such as chemicals, catalysts, utilities, maintenance and salaries. This surplus, referred to as the refining margin, should be sufficient to cover investment costs such as interest on capital employed and plant depreciation as well as to generate a profit for the refining company.

While total demand for petroleum products was relatively flat in the late 1970s and early 1980s, this concealed very divergent trends for different products. As the price of crude oil increased, the economic advantage previously enjoyed by heavy fuel in the electricity generating market was eroded, and much of this market was lost initially to coal and nuclear energy, and subsequently to natural gas. At the same time there was no such easy substitution in the case of transportation fuels, and as economies recovered from the shocks of 1973 and 1979 growth rates in demand for gasoline, automotive diesel and aviation kerosene (AVTUR) resumed. This disparity in growth led to surplus production and consequent weak prices for heavy fuel oil and to corresponding underproduction and relative price strength for the more valuable lighter products.

In effect, the natural distillation yield of most crude oils no longer provided the industry with a yield pattern consistent with market demand. This was partly mitigated by the fact that newly available crude oils from the North Sea and West Africa tended to be lighter and sweeter than traditional Middle East crude oils, but nevertheless there became an increasing economic incentive to minimize heavy fuel oil and residue production and to maximize production of the more marketable light products.

This, in turn, led to increasingly wide variations in refinery margin, with hydroskimming refineries which have little scope to upgrade residue frequently seeing negative margins while the more complex refineries were making margins that fluctuated from the highly satisfactory to around break-even. This resulted in the closure of many of the older hydroskimming refineries, especially in Europe, and in the upgrading of many other refineries by the addition of secondary units, the cost of which was frequently greater than the original cost of the refinery.

The objective of this upgrading was principally to modify the yield pattern of any given crude oil by cracking the heavy fractions (large carbon-rich molecules) into lighter fractions which would boil off in a distillation column (smaller molecules with a relatively greater proportion of hydrogen to carbon). There are a number of processes which can be used for this purpose, as described in Chapters 4 and 5 in Volume 2.

In Western Europe the chosen route tended to be the construction of fluid catalytic cracking (FCC units), often accompanied by HF alkylation and other secondary units to produce products, particularly gasoline, meeting required specifications. In Asia, however, the construction of hydrocracking units tended to be preferred in many cases. This difference is partly explained by the different development of the two markets, the major demand growth in Europe being for gasolines, for which the FCC route may be optimal, whereas in Asia the fastest growth in demand was for middle distillates and aviation kerosene, in the production of which the hydrocracking process has more flexibility, and thus may economically be preferable despite its generally higher capital and operating costs.

The priorities of technological development in this period in the refining sector were therefore heavily biased towards improvement of refinery upgrading processes. Relatively small improvements in the precision of separation of different refinery 'cuts', in process thermal efficiency or in the yields of high-value products were not the stuff of dramatic, headline-making technology, but in aggregate made a vital difference to the refinery bottom-line profit.

Many of these developments were derivative. From the work of materials scientists, we learned of the properties of new bimetallic and shape-selective catalysts and applied them to applications within our processes, extending the effective life of expensive catalysts, reducing the need for down-time when replacing or regenerating catalysts and improving product yields. From computer scientists and instrumentation engineers, we learned of developments in computer control systems and of remote digital instrumentation and applied them to our refineries, permitting the control of the refinery from a single central control room and marked improvements in process optimization. Process engineers thought more closely about the optimization of flows to use any waste heat in preheating crude oil or other feedstock and of reducing energy loss through heat exchangers where possible; this was not blinding new technology, but the intelligent and cost-effective application to the oil industry of work largely undertaken by academics and in the chemical industry.

Throughout the late 1980s and the 1990s, economics remained one of the key drivers of technology in the oil and gas industry, although the emphasis continued to change. Throughout most of the world, growth in demand for petroleum products remained relatively subdued; only in the Asia-Pacific region was there strong growth, and this was largely curtailed by the economic and financial downturn which hit that region in mid-1997. Although, for much of this period, Iraq was out of the market as a major Middle East producer as a result of UN sanctions, and the Middle East could hardly be described as totally stable, there was nevertheless a perception in international oil markets of adequate and secure supply, and thus the predominant pressure on oil prices was generally downward.

The other major politico-economic feature of this period was the break-up of the Former Soviet Union and the COMECON system, and the liberalization of oil and, more particularly, gas markets in many other areas of the world. In general, this restructuring did not require the evolution of new technology, but it did require massive investment in these new areas of opportunity by the international oil industry, in many cases transferring to resource-rich but investment-starved regions the technologies proven in the international industry.

The results of such technology transfer have been mixed. There have certainly been very many successful projects, in particular those involving licence or joint venture arrangements between international oil service companies and their indigenous counterparts. In many cases, however, technology has been transferred without the necessary culture changes accompanying it, and the results have been disappointing. In some cases there has not been the resource of skilled or trained staff to operate the technology to best advantage or to maintain it; in other cases, particularly amongst state-controlled companies, there has not been the political will to reduce head count or to adapt working practices so that the economies achieved by the adoption of such technology in the international industry can be replicated.

One welcome feature of the industry's efforts to control costs during this period has been that of industry-wide co-operation on cost reduction initiatives. The two best known of these are CRINE (the Cost Reduction Initiative for a New Era) in the UK and NORSOK in Norway, but these two pioneering programmes have been imitated with varying degrees of success in a number of other countries or regions.

The essence of such initiatives is one of identifying best industry practice and promoting its adoption, whether it be technology or contractual practice, throughout the industry. (This, of course, is also very much the *raison d'être* of much of the work of the Institute of Petroleum in its technical committees, its publications such as its codes, standards and *Modern Petroleum Technology*, and its conference and discussion meeting programmes; for this reason, the Institute has welcomed CRINE and similar initiatives and continues to seek opportunities for ongoing co-operation with them.)

Cost reduction initiatives involve the development of standard specifications where these are appropriate and where the use of cheaper standard specified equipment can contribute to a reduction in project lead times as well as in costs.

In the past, an oil company might have precisely specified a pump or a compressor, an elaborate procurement procedure would have been utilized, an order placed and the equipment built and delivered to meet that order. Today, it is much more likely to specify what are the functional requirements (such as flow capacity) of the pump or compressor, identify what standard equipment is available to meet those requirements and purchase accordingly 'off the shelf'. This not only reduces design and procurement time, but also greatly reduces cost and avoids the necessity to hold in inventory spares of non-standard items which might infrequently or never be called upon.

Cost reduction initiatives, of course, can equally apply to professional and other contractual services. For example, most third-party service contracts contain broadly the same headings, although the detailed provisions may differ. Yet in the past each contract has often been individually negotiated by the parties, frequently involving their lawyers or contract negotiators. Some contracts are sufficiently unusual to require such 'bespoke' legal intervention, but in most cases there would clearly be a considerable cost and time advantage in contracting on standard contract terms with which the industry, its contractors and suppliers are familiar, just leaving a number of specified items such as price and delivery date to be negotiated between the parties and inserted into the standard contract form. CRINE and NORSOK, in particular, have both devoted a considerable effort in recent years to the development of standard contracts, and it is the prevailing view that these have made a significant contribution to the cost reduction process.

The issue of cost reduction initiatives has been discussed at some length because they are central to the technical ethos of the oil industry in the closing years of this millennium. Much of the technical resources of the industry have been devoted to standardization and to simplification, where previously each company might have been less productively working on its own differentiated technology and on 'improvements' to designs and processes which might present sound and elegant engineering solutions without really adding any significant functional or economic advantage.

Economics will inevitably continue to be one of the key drivers in the development of petroleum technology and the need to find ways of conducting our business at lower cost is likely to remain the paramount economic driver, particularly while the oil price remains relatively low.

3 THE ENVIRONMENTAL CONSTRAINTS

Apart from economics, the other main driving force behind the development of petroleum technology over the past 20 years has been the environmental and safety issues affecting the industry. This reflects the much greater emphasis on factors relating to health, safety and the environment (HSE) in the oil industry in recent times and the much greater preoccupation of senior operational management with these issues, itself partly reflecting a much greater degree of legitimate public and media interest.

These issues can be categorized under three headings:

- providing products to the high specifications now required by our customers, by the public and pressure groups and by regulators (both domestic and, increasingly, supra-national)
- conducting operations as an industry in an environmentally responsible and neighbourly manner, particularly as regards discharges to the atmosphere and to the marine environment, and
- providing a safe working environment for employees, contractors and the customers who utilize products.

Each of these has a significant influence on the prioritization of technological development within the industry.

The specification of petroleum products has always been a matter of gradual improvement. In the period up to the late 1970s there was an element of performance competition amongst the major oil companies, but since that time this element of competition has largely disappeared and, in respect of petroleum fuels at least, it has become much more of a commodity market meeting industry standard specifications. Where companies have sought to distinguish the quality of their fuels in recent years it has rarely been on the basis of performance but more usually on the basis of environmental quality. (This is very different from the lubricants markets where, particularly in industrial and special lubricants, technical formulation, functional performance and application advice remain key elements in the marketing of such products.)

Public concern on issues such as lead or aromatics in gasoline, the sulphur level of products, and particulates from diesel engines has been reflected in regulation and legislation at the level of the individual country or, more frequently, at supranational level—such as the Auto Oil initiative within the European Union. To the extent that such regulation is based upon sound science and is realistic and cost-effective, the industry has been generally supportive.

However where quality standards are imposed which are excessive in stringency, and it cannot be seen that any environmental benefit is being achieved commensurate with the cost incurred in achieving the marginal extra quality standard, the industry's reaction has been more ambivalent. It is perhaps too easy, despite the belief that a particular measure will not achieve an environmental benefit commensurate with the investment required to achieve it, to shrug our collective shoulders and say that making that investment is part of the cost of our licence to remain in business, and that ultimately customers will pick up the bill for it.

Meeting the quality standards that our customers and regulators demand requires development of the technology of the oil industry on two fronts; first, the need to develop the products and, second, the processes whereby those products can be manufactured consistently to the required standards at an economically acceptable price.

The development of products that meet the required quality standards has not generally been unduly difficult; where problems have arisen they have frequently arisen from the need to 'trade off' one characteristic against another. These issues are discussed in relation to the principal products in Chapters 19–23 of Volume 2.

More stringent product specifications in turn require continuous development in the technology of testing products, so that there are repeatable and objectively verifiable standards against which product quality may be determined. As the number of parameters or characteristics which must be determined in a given product increases, as the automation of testing progresses and as tests must be developed to detect ever smaller concentrations of a particular substance in a product, the need to improve test methods and to standardize the best practice internationally remains a major technological task. The Institute of Petroleum, together with the ASTM in the United States, has long been at the forefront of this process, and continues to play an active role in developing and publishing Standard Test Methods, as well as in ensuring that the industry's views are fully considered in the International Standards Organisation (ISO) where, today, many of these standard methods are endorsed on an international level.

The need to develop refining processes that can produce these products to the required quality specification at an acceptable cost has been more of a challenge. There has not generally been a need to develop radically new refinery processes, but for steady evolution and development, such as the formulation of improved catalysts, which improve yields and allow refinery units to be run at greater severities. In most process development, the key objectives have been to ensure consistent quality, to improve process yields and to improve process economics. These developments are reflected in Chapters 3–6 of Volume 2, where the current state of refinery process technology is ably described.

The second series of environmental issues driving the development of petroleum technology are those connected with the need for the oil industry to conduct its operations in an environmentally responsible and neighbourly manner. This is a wide range of issues, covering everything from greenhouse gases to major tanker accidents, such as that of the *Sea Empress*, to the question of decommissioning or abandonment of redundant offshore installations, as exemplified by the *Brent Spar*. For convenience, they may be grouped according to which element is affected—land, water or atmosphere.

Land may easily become polluted by seepage of hydrocarbons. Both public opinion and regulatory codes today require steps to be taken to avoid such seepage to an extent way beyond anything that was envisaged 20 years ago. This has made two demands on the development of petroleum technology: First, how can future seepage be prevented and, second, how can existing sites be remediated?

The prevention of future seepage is only partly a matter of developing new technology; it is principally a matter of securing the widespread understanding and adoption throughout the industry, its contractors and its customers of best practice. However, technology has assisted, for example through the availability of new impervious materials for underground tanks and pipes and of better monitoring, measurement and loss control systems.

Where in the past installations such as service stations and distribution depots were not built to such standards, a problem of remediation exists when those installations are no longer required. Practice in the industry is usually to demolish the installations completely, but this may still leave the problem of land, particularly top soil, contaminated by hydrocarbon seepage. Frequently, the extent of such seepage is hard to estimate until demolition of the installation is completed—a problem largely overcome by a range of new chemical, physical and electronic technologies which have been developed to measure the extent of hydrocarbon contamination *in situ*. Until recently, the only way in which contaminated top soil could be treated was by digging out and removal from site for treatment, and replacement of the top soil by uncontaminated or treated material, but recent developments in microbiology have offered the prospect of oil-consuming microbes which work on the contaminated soil and can bioremediate it *in situ*.

Pollution of water has posed a larger number of environmental challenges to the oil industry. In refineries and other process plant it is necessary to treat all water emanating from the plant, so that its quality when returned to the natural environment is at least as clean (and in some cases cleaner) than when entering the plant. This applies to process water, including that used for cooling, and to run-off water such as rainfall on the plant site. Most modern refineries use much less process water than 20 years ago; this is principally because of the need to look closely at the thermal efficiency of refinery processes and to utilize waste heat where possible in pre-heating other process streams, and also because of the trend to use air cooling rather than water flow in heat exchangers. Nevertheless, there is still the need for substantial investment in water treatment facilities at most of the industry's plants. Technology developed in the water treatment industry and adapted to the needs of the oil industry allows water to be returned to the natural environment to a very stringent quality specification.

The other aspect of water pollution is where oil escapes from a tanker or an offshore oil seepage and enters the sea. Incidents such as those involving the *Sea Empress*, the *Exxon Valdez* and, some years previously, the *Ekofisk Bravo* production platform blow-out are all remembered by the public years after the incidents took place, and shape the public perception of the industry. Over the past 20 years the oil and shipping industries, together with regulatory authorities, have co-operated closely to improve both safety and operating practice in the oil shipping business. Technology has played its part in this, although many of the key developments have been more in the technology of shipping and marine electronics, such as double hull construction and GMDSS, than in petroleum technology.

The oil industry has, however, been supportive and actively involved in the developing technology of oil pollution prevention, clean-up and remediation. This has included research and technological development of equipment and techniques for containment and recovery of spilt oil, such as booms and skimmers, and the formulation of dispersants which are less toxic to the marine environment than those previously used. Many of the most acute marine pollution problems concerning the oil industry relate to oil pollution of intertidal areas and estuarial marsh lands, where the ecological damage is often most acute; the oil industry has been active over the past 20 years in co-operating with marine biologists and ecologists on a wide portfolio of research to understand fully and to learn how optimally to treat such problems.

The offshore exploration and production business has also addressed a wide range of marine pollution issues, from the deposit on the sea bed of drill cuttings (particularly those from wells where oil-based muds were used for drilling), and the effects of subsea pipelines, to the decommissioning of redundant platforms and other structures. This last issue is one on which the debate still continues but, at the very least, it is now clear that for the majority of platforms complete or substantial removal will be required. This will involve further evolution of the technology involved in offshore dismantling and subsequent onshore reclamation or destruction.

Atmospheric pollution is also a major issue for the oil industry and one which has driven the direction of our technological development. Concern on this has, as was discussed above, contributed significantly to the way in which the specification of petroleum products has developed, particularly in relation to the progressive reduction in maximum permitted sulphur levels in petroleum products, and the maximum permissible levels of aromatics in gasoline or of particulates from diesel engines.

The industry has also had to reduce the levels of emission from its own operations, both refining and exploration and production. In oil production today it is no longer acceptable to flare gas as a routine operation; not only are there environmental considerations, but the economics also dictates that a potentially valuable fuel should not be wasted.

This has promoted much technological effort devoted to ways of utilizing associated gas where there is no obvious commercial market for it. One example is the reinjection of the gas for reservoir pressure maintenance; advances in reservoir simulation modelling, as described in Chapter 7 of Volume 1, have led to great improvements in recent years in the ability to predict the results of gas reinjection and in permitting the optimization of development programmes to make best use of this capability, and to maximize long-term economic benefit.

Where reinjection is not possible, other alternatives can be considered which would not have been thought possible only a few years ago. For example, several long distance subsea pipelines are being considered (such as the project to gather gas from the Hides and Kutubu fields in Papua New Guinea for pipeline transmission to Queensland, Australia); when first considered a few years ago such projects were not regarded as feasible, but today new technology in offshore pipe-laying has improved the economics and new technology to prevent the formation of hydrates in such pipelines has resolved one of the main potential operational problems.

Particularly in the Asia-Pacific region which, over the long term, is likely to resume its position as an area of prime growth in energy demand and which has substantial reserves of natural gas, much of the oil industry's research and technology spending in the next decade is likely to be devoted to the better utilization of natural gas, with renewed interest in the development of liquid automotive fuels and middle distillates derived from natural gas. Many of the methanol-based projects constructed in the 1980s have demonstrated that such projects are economically very sensitive and are only likely to proceed to commercialization against a scenario of future higher oil prices or scarcity of conventional crude oil and products.

Discharges to the atmosphere from our refineries and onshore facilities are also much reduced as a result of regulation, 'good neighbour' policies and enlightened economic self-interest. One example of this is the elimination from most refineries of the flare stack, which was a feature of such plant 20 or 25 years ago. Refinery tail gas is now used as refinery fuel, a process facilitated by the development of technically advanced multi-fuel boilers usually associated with package electric generating equipment and the capability to sell into the public supply grid any surplus electricity generated. Flare stacks have usually been replaced by clean-burning ground flares for use in emergency relief or during start-up of units.

The third and final group of HSE issues which has influenced the development of petroleum technology is that concerned with the need to provide a safe working environment for our employees, our contractors and the customers who utilize our products.

It has been the experience not only of the oil industry but also of other potentially hazardous industries, such as shipping and the nuclear industry, that many of the advances in technology—and certainly in regulation—are incident-driven. To take an example from the shipping industry, the heavy loss of life on the *Titantic* was the principal driver for the development of various new marine engineering technologies, as well as being the catalyst for major international regulatory intervention. This has certainly been the experience of the oil industry, where a number of incidents or accidents have yielded lessons that we have sought to apply for the future. Perhaps the most significant of these in the past 20 years in the oil industry was the *Piper Alpha* disaster; the industry learned much both from its own analysis of the accident and, more particularly, from Lord Cullen's thorough and meticulous inquiry, report and recommendations.

This process of learning by experience is no longer acceptable in high-risk industries where the results of even one massive accident cannot be contemplated. A whole new science of safety engineering has developed in the past 20 years, which makes full use of statistical and probabilistic techniques, and which has been greatly assisted by the development of powerful computer program that allow the consequences of an accident or a structural failure, or some similar event, to be simulated on screen and suitable safety limits derived without physical experimentation.

This new approach to safety has also led to a complete change in thinking for both industry and regulators, initially in the British and Norwegian offshore but now with growing application in other areas of the world. Previously, much of safety certification and assurance was based on a prescriptive rule observance regime; provided that