ROYAL ACADEMY of ENGINEERING

Design principles The engineer's contribution to society

The Royal Academy of Engineering's Visiting Professorship Scheme in Principles of Engineering Design appointed skilled and successful practising engineers to contribute to the teaching and development of undergraduate courses. The professors appointed not only expressed their enjoyment of this opportunity, but also expressed an interest in formulating fundamental design principles. We decided to try and define these principles. Engineers contribute considerably to the quality of life in society and it is important that they articulate their role clearly and firmly. We hope that a definition of these principles will enhance this contribution.

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The four objectives of the Corporate Plan of The Royal Academy of Engineering for the years 2001-2004 can be summarised as:

‘TO MAINTAIN A CRUSADING, LEADERSHIP ROLE... RECOGNISING THE ENGINEER’S RESPONSIBILITY FOR LEADING DEBATE AND ACTION ON A WIDE RANGE OF IMPORTANT ISSUES OF NATIONAL INTEREST AND IMPORTANCE WHICH HAVE AN ENGINEERING DIMENSION, SUCH AS SUSTAINABILITY, BIOMEDICAL ENGINEERING AND EMERGING DISCIPLINES...’

‘TO SUPPORT ENGINEERING EDUCATION AND TRAINING AT ALL LEVELS...’

‘TO WORK TOWARDS GREATER CROSS FERTILISATION BETWEEN INDUSTRY AND ACADEME...’

‘TO PROMOTE THE IMPORTANCE OF ENGINEERING NATIONALLY AND INTERNATIONALLY;
TO IMPROVE THE QUALITY OF ADVICE TO PARLIAMENT AND MINISTRIES;
TO PROMOTE GREATER UNDERSTANDING AND INTEREST IN ENGINEERING; ...’

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A broader role for engineers in decision-making

ANY ENGINEERING PROJECT INVOLVES A COMPLEX DECISION-MAKING PROCESS – DESIGN – THE SUCCESS OF WHICH IS MEASURED IN THE EFFECTIVENESS OF THE PROJECT. ENGINEERS NEED TO PLAY A MAJOR PART IN THE EARLY STAGES OF DECISION-MAKING. AN UNDERSTANDING OF BASIC DESIGN PRINCIPLES HELPS TO ENSURE SUCCESS

The Royal Charter of the Institution of Civil Engineers describes the role of the engineer as that of:
"...HARNESSING THE GREAT FORCES IN NATURE FOR THE USE AND CONVENIENCE OF MAN."
(Today we would add: "with due consideration of environmental and economic sustainability.")

Traditionally, engineers are trained to deliver products, projects or services to fit some specified requirement. They work to a required performance and quality, within a given time and budget. But the creative and analytical skills of engineers are frequently used only to develop or make practical the decisions of others. The importance of engaging engineers in the early decision-making processes of a project is frequently not appreciated, and major decisions are left in the hands of the non-engineering professions – the politicians, lawyers, accountants or marketing experts. This is despite the fact that these decisions may require not only understanding the engineering possibilities, but also knowledge and experience of potential environmental and social consequences.

Engineering decisions have an enormous impact upon the quality of life in the global community – for example, the social and economic effects of building dams in developing countries or new airports on the outskirts of cities. It is essential, therefore, that engineers play a full and significant role in ordering the affairs of society, not merely as technicians carrying out the instructions of others. It is a major objective of The Royal Academy of Engineering to help engineers become more aware of the contribution that their abilities can make to primary decision-making activities, affecting the very nature of the tasks to be achieved.

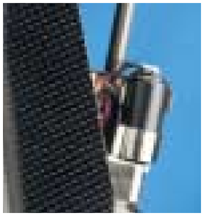
Role of design

Clearly, at the core of decision-making in any technical project is the design strategy. It is the essential creative process of engineering – different from science – which calls for imagination, application of technical expertise and experience, and skilful use of materials. Paradoxically, however, because engineers are so good at delivering the given requirements of the project, they are often not involved in the design element of the process, which is seen as part of the development of decisions made by others. This means that engineers are not participating in primary decision-making as usefully as they could.

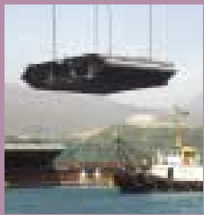
It is important that practising engineers and engineering students understand the synergy between engineering design and high-level decision-making. Here, it is helpful to formulate some principles – general stages in the design process, used by all experienced designers, but not always consciously articulated. Students should be shown how to tackle design projects systematically, integrating detailed technical competencies as required by these fundamental principles. It is particularly important that the general and interdisciplinary aspects of design be demonstrated at every stage in the design process.

Henry Palmer, the distinguished first President of the Institution of Civil Engineers, at the inaugural lecture of the Institution on 2 January 1818, said:

"THE ENGINEER IS A MEDIATOR BETWEEN THE PHILOSOPHER AND THE WORKING MECHANIC AND, LIKE AN INTERPRETER BETWEEN TWO FOREIGNERS, MUST UNDERSTAND THE LANGUAGE OF BOTH, HENCE THE ABSOLUTE NECESSITY OF POSSESSING BOTH PRACTICAL AND THEORETICAL KNOWLEDGE."



This booklet explains those principles and gives some examples of how they are used.

Design principles

AN AWARENESS OF FUNDAMENTAL DESIGN PRINCIPLES ENABLES ENGINEERS TO ENGAGE IN THE HIGHEST LEVEL OF DECISION-MAKING – TO WHICH THEY CAN THEN BRING THEIR PROFESSIONAL SKILL AND TRAINING

Design principles have in the past focused on the technical and scientific rules underpinning the delivery process. Indeed, good engineering design involves many parameters upon which the success of the project depends, each of which has its own subset of laws, standards, practices, codes and regulations. However, underlying all these more specialised constraints and directives are even more fundamental principles – related to the original decision-making process – which provide the total context for good design.

These principles may be well known to experienced designers, but may not have been communicated to students, yet understanding them is essential if design decisions are to produce desirable results. They are not the purely scientific, axiomatic principles, such as the laws of statics or thermodynamics, which are already part of the engineering curriculum, but derive more from experience, practice or pragmatism. They are the very substance of professional engineering judgement.

Statements of principle

Engineering design encompasses three key stages of realisation.

NEED – all design begins with a clearly defined need

VISION – all designs arise from a creative response to a need

DELIVERY – all designs result in a system, product or project that meets the need

Some case studies

To demonstrate the relationship between the three basic design concepts – need, vision and delivery – and the rules specific to a particular discipline, four high-profile projects have been selected from different fields. The examples chosen represent a wide range of engineering designs from single, speciality products to large-scale projects.

They are:

- An intelligent prosthesis developed by Chas A. Blatchford & Sons;
- The Tsing Ma Bridge designed by Mott MacDonald;
- An asthma inhaler developed by IVAX Pharmaceuticals;
- The Trent aero engine developed by Rolls-Royce.

Need All design begins with a clearly defined need

This first principle requires recognising and understanding the nature of society, economics and humanity's needs. Reason, compassion, service and curiosity all contribute to the definition of need.

Defining the need is a multidisciplinary task – carried out by either a selected team of experts, or by an experienced and multi-skilled individual. The skills required are not exclusively engineering, but include economic and political skills, and knowledge of marketing and industrial management.

It is important that a clear definition of the need is formulated, with the reasons for the decisions given. There must be commitment at the highest level, and maximum feedback from earlier developments.

Vision All designs arise from a creative response to a need

This second principle is the conception and management of a creative vision to meet the need. It requires the ability to think laterally, to anticipate the unexpected – and to appreciate the aesthetics of problem-solving as well as the material aspect. The ethos within which the problem is being addressed must be understood.

Design development is an iterative process, so a good relationship with the need-defining team is essential. The perceived needs may change during this stage. Evaluation of the concept requires a full understanding of the need as formulated, as well as the delivery constraints likely to affect the design formulation. The designer also needs to know about market constraints and the production processes.

The controlling team or individual must have access to all necessary specialist advice. On larger-scale projects, the management of the various inputs must be strong and effective without inhibiting creative thinking. On smaller projects, good self-discipline is necessary to ensure that the development does not deviate from the perceived need. External advice must be well coordinated, and its role in the design development understood. Specialist consultants must appreciate the total context and aims of the project, which should not be confused by individual disciplinary objectives.

Delivery All designs result in a system, product or project that meets the need

The final principle involves delivering a solution to a recognised need. This requires assembling and managing resources and team members with the necessary skills and knowledge needed to create an appropriate and efficient design.

As the scale and complexity of projects increase, so does the need to define a clear management structure and the relationship of the design components to the whole project. Smaller projects may permit more flexibility, but engineers need to take care to avoid making too many alterations on the basis of manufacturing expediency. The original and formulated aims and proposals should provide the platform for the production activities.

There should be regular team reviews to ensure continuity of concept, as well as testing and management to ensure a high and consistent quality in the end product.

An intelligent prosthesis – Chas. A. Blatchford & Sons

Need

Traditional artificial limbs require a significant effort by the user and make it very tiring to walk quickly. The aim of this project was therefore to improve how an artificial limb worked. Blatchford identified two needs – that of the user and that of the supplier.

The supplier's need was based on market considerations. In this case, an experienced manufacturer (Chas. A. Blatchford & Sons Ltd) provided the skill and resources, but in collaboration with both the user and the service provider via the National Health Service.

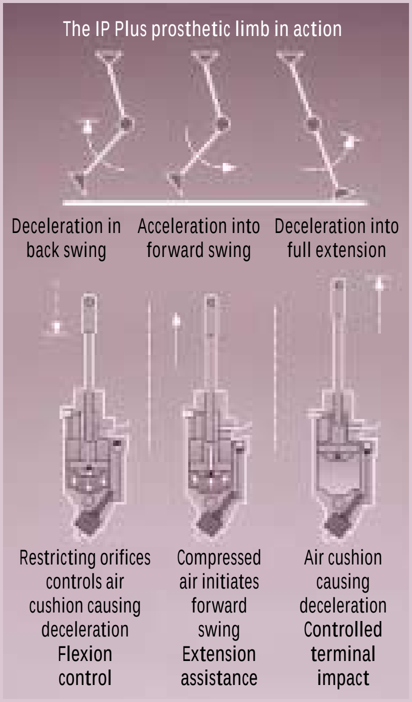
The user's rehabilitation need is satisfied by a prosthesis that could change characteristics with walking speed. Interest in working towards this end was stimulated by developments in technology – particularly the possibility of using microprocessors to control the mechanical components in the artificial joint. This also required a change in manufacturing culture – away from manual skills to systems engineering. Support from senior management ensured that the work would be implemented.

Vision

A small multidisciplinary team of scientists and engineers from Blatchford's research and development department provided the expertise and the willingness needed to carry the project forward. A creative, innovative and enthusiastic exchange of ideas, particularly in exploiting the latest developments in control and sensing systems, led to these techniques being integrated into an 'intelligent' prosthesis. The prosthesis would learn the user's walking style, and adapt the movement of the limb to suit a change of pace, thus considerably reducing the physical effort required.

Delivery

The most important step in delivery was to assemble a team dedicated to producing the improved prosthesis (IP Plus). Members of the team represented all the disciplines – electronic engineering, mechanical engineering, management, prosthetic fitting, marketing, and customer support – as well as the various manufacturing skills. The team also worked with test consultants and government agencies.



The supply organisation was developed during the production stage to enable a move from specialist subcontractors and suppliers to manufacture by Blatchford, by increasing the in-house skills and facilities of the principal manufacturer. The team recognised that this was a further step in the development of even more effective prostheses.

Feedback from users has enabled continuing improvement of the prosthesis. The skills developed during the project are now being applied to other products.

Chas. A. Blatchford & Sons Ltd, based in Basingstoke, is a family-owned company which has been making prosthetics for more than a century. The success of its products relies on continuing innovation in design and materials. The company has won numerous awards including the Duke of Edinburgh's Designer Prize, three Queen's awards for technological achievement, a Design Council Award and The Prince of Wales Award for Innovation.

The IP Plus prosthetic limb and programmer

Making the most of the IP Plus

A breath-actuated metered dose (asthma) inhaler – IVAX Pharmaceuticals

Need

Asthma sufferers rely heavily on pressurised inhalers that deliver a metered dose of a prescribed drug to relieve and control symptoms. However, many patients find them difficult to use correctly, with the result that they do not receive the correct dose. An experienced senior pharmacist, John Bell at IVAX Pharmaceuticals, realised there was, therefore, a need for a breath-actuated inhaler that would automatically synchronise the intake of breath with the release of the drug dose. His multidisciplinary skills allowed him to assess the market for such devices, as well as the needs of patients, and his seniority meant that he had the necessary authority to carry the project through to completion.

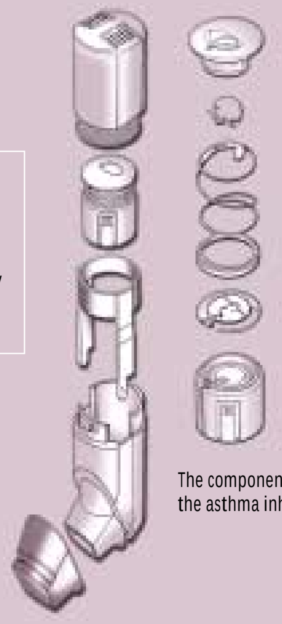
Vision

IVAX took up the challenge of implementing the concept. An holistic view of the project was essential, together with access to all the skills needed for a full definition of the final product. Flexibility of creative thinking was important. IVAX's development team consisted of the 'specifier' who defined the need, and the creative 'inventor' (a clinical scientist, Dr Ray Bacon) who translated the need into a concept. The design had to be flexible enough to use with different drug formulations and combinations of propellants. It also had to allow for changes in presentation to suit local preferences around the world. IVAX also recognised at this stage that it could create a professional product only by out-sourcing expertise.

Delivery

A small core team – a pharmacist, a clinical scientist and a development engineer (Mike Holroyd) – managed by the specifier, coordinated the delivery. It subcontracted the development work to experienced consultants, and secured external advice on a variety of essential issues such as regulatory matters, marketing, sales, clinical trials and personnel. Some flexibility was introduced into the manufacturing process, whilst adhering to the concept developed during the 'vision' stage in design. This was a key element in enabling continued development to produce further generations of similar devices.

IVAX Pharmaceuticals (formerly Norton Healthcare) is a subsidiary of the IVAX Corporation based in Miami, Florida. It makes generic pharmaceutical products, particularly in the respiratory area. IVAX's Easi-Breathe breath-actuated asthma inhaler won The Royal Academy of Engineering's prestigious MacRobert Award in 1998.



The components of the asthma inhaler

1 A cross-section of the Easi-Breathe inhaler, showing the pneumatic actuation mechanism above the aerosol can. When closed, the cams on the dust cover hold the actuation mechanism clear of the can.

2 The primed inhaler with its dust cover opened. The vacuum in the pneumatic actuation mechanism restrains the spring from pushing the can down.

3 The inhaler after actuation. When the patient breathed in, the flap-valve opened, releasing the vacuum and allowing the spring to push down on the can and actuate the valve, thus releasing a dose of medication.

The Tsing Ma Bridge – Mott MacDonald

Mott MacDonald is a global design consultancy engaged in development across all sectors – from transport, energy, water and the environment to building, industry, communications and education.

Need

There was a need to move Hong Kong's airport away from the heavily populated urban centre where expansion to meet growing demand was constrained and landings were difficult. This need was defined in outline by the client – the Hong Kong Government – formulating the exact requirements for extended transport facilities, and residential and other developments associated with the new airport.

The definition of need for such a major project was a design exercise in its own right. Many interested parties and specialists were consulted and engaged, and the development of the brief needed to be well-organised. The overall need comprised a series of linked secondary requirements within the affected sectors – air, road and rail transport, cargo shipping and ferries, residential and commercial development, and recreational facilities. The team director therefore had to coordinate these requirements and assemble the appropriate skilled team. This team also considered the context and location of the major facilities.

The studies confirmed the need for a new airport, and that it should be located on Hong Kong's Lantau Island. This location had neither road nor rail links to the urban centre of Hong Kong, which meant that a fixed link – a tunnel or bridge – connecting the island to Hong Kong was required.

Although the design was promoted and directed by the client, its execution was dependent upon inputs from specialist consultants in many areas – economic, planning, transport, engineering (marine, tunnels, bridge, highways, railways), environment and risk assessment.

Vision

The project's aim was to provide the fixed link – as part of the overall plan for 10 Airport Core Projects (ACP). The design team, steered by the client, and led by Mott MacDonald, brought together the various requirements in the context of the overall ACP programme. It addressed the engineering challenges to providing a long-span suspension bridge that could withstand and remain operational in typhoon conditions, and could carry an express highway and high-speed railway. These challenges included the operational requirements of the railway, the nature of the subsoil, the marine environment, weather and climate, cost, constructability, and minimising hazards to the bridge and shipping. Choosing the right design required a creative team effort to identify several possible solutions, and evaluate development of the preferred option to confirm its feasibility before being formulated and made ready for delivery. The final design was for a multi-purpose, double-deck, suspension bridge carrying both road and rail traffic.

Delivery

To implement the project, Mott McDonald developed the agreed outline design for the bridge into a detailed design. The company set up and coordinated a team of designers and technical specialists, while establishing and maintaining independent checks and procedures for quality assurance. The team prepared the contract documents and supervised the project throughout construction. This entailed close cooperation with the contractors and with many specialist subcontractors and suppliers throughout the whole contract period.

Tsing Ma's innovative streamlined vented two-level deck designed to withstand typhoon winds

The main picture shows the bridge's 1000-tonne deck units being lifted into position using strand jacking techniques. The left inset shows the location of the bridge in relation to the new airport and Hong Kong; the right-hand photo shows one of the steel saddles, which support the main suspension cables at the top of the 206-metre high towers

The Trent aero engine – Rolls-Royce

Need

Rolls-Royce recognised that there was a continuing need to review and develop its existing successful engine designs for aircraft, ships and energy generation to meet ever-increasing demands for more power, and better efficiency, reliability and safety. For example, on the aerospace side of the industry, new generations of ever larger jets needed more thrust; demands for enhanced fuel efficiency required the use of lighter materials; while continuing needs for lower pollution and noise levels, and longer lifespan for the engine, would be satisfied by improved design.

A *small core* multidisciplinary team was able to define a product proposal that integrated the perceived market needs, the company capability and the business opportunities.

Vision

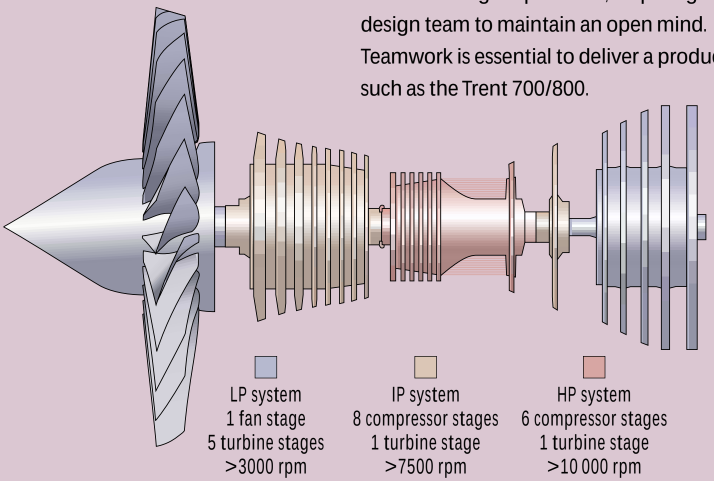
The Trent aero engine, which is a three-shaft turbofan, was originally developed in the 1960s with this approach in mind: the design can be adapted to meet changing requirements. For example, the Trent 700 and 800 engines – used in the A330 Airbus and the Boeing 777 respectively – emerged from several requirements, identified during the need phase. This included the possibility of improved components and new technology from suppliers, internal constraints of Rolls-Royce, and ever tighter regulatory requirements.

The vision that further and significant developments were possible was built in as part of the design-team culture. In the case of engineering design, the vision is a continuous cutting-edge awareness of changing demand and technological potential, requiring the design team to maintain an open mind. Teamwork is essential to deliver a product such as the Trent 700/800.

Delivery

Rolls-Royce uses well-defined established engineering procedures to guide and monitor the delivery process. A Project Director was essential to manage the increasing scale of the project and to coordinate the growing multidisciplinary teams involved in delivering the product. Continuous liaison with the customer and supplier-chain organisations as well as the regulatory bodies is also an essential part, as is the need to build prototypes to verify that the design meets requirements.

Rolls-Royce produces one of the broadest ranges of gas turbine aero engines in the world, powering applications from the smallest business jets to the largest airliners. The company also supplies engines for marine propulsion and power generation.



All Trent and RB211 engines are based upon the three-shaft principle. This unique design concept means that the engine is lighter, shorter and stronger. Each shaft can be scaled independently to match specific aircraft thrust requirements.

Main photo: Rolls-Royce Trent and RB211 engines on the company's assembly line at Derby
Inset above left, a Trent 800-powered Boeing 777; above right, two of the four Trent 500s which power the Airbus A340

Visiting Professors in Principles of Engineering Design

THE ACADEMY IS PLAYING AN IMPORTANT ROLE IN PROMOTING THE ROLE OF ENGINEERING DESIGN AND THE PRINCIPLES EXPLAINED IN THIS BOOKLET

The teaching of design principles has an integral place in the education of all engineers. This is recognised through a scheme operated by The Royal Academy of Engineering called the Visiting Professors in Principles of Engineering Design. It aims to help UK universities teach design to undergraduates in a way that is more relevant to real industrial practice.

The scheme was started in 1989 in response to a widely-held belief that education in engineering design was too theoretical. The Academy decided to sponsor universities to appoint experienced industrialists, with backgrounds in design and technology or project development, to work as Visiting Professors (VPs) to help reshape the syllabus for teaching design.

The appointments are for 3 to 5 years with a regular commitment to a university typically of about 15 days a year. About 150 VPs now work in some 45 academic institutions, demonstrating and transmitting to students and staff the essential characteristics of engineering design, based upon their own experience and success.

The scheme has several benefits, which reinforce the Academy's objectives as laid out in its Corporate Plan.

- The VPs are able to demonstrate, through their own experience, the role engineers can play in the early stages of design – that of identifying need and conceptual design.
- They are able to help develop and teach design methodologies directly related to industrial best practice.
- They can further closer collaboration between academe and industry, not only by their own example, but also through staff secondments between the two sectors.
- Finally, the need to attract first-class students, both men and women, into engineering, and to develop a well trained national force of professionals is constantly reiterated by The Academy, the Engineering and Technology Board and other professional institutions. The Visiting Professors, all with track records of success in their own fields of engineering, are well-equipped to play a significant role in this work.

The Royal Academy of Engineering

The objectives of The Royal Academy of Engineering are to pursue, encourage and maintain excellence in the whole field of engineering in order to promote the advancement of the science, art and practice of engineering for the benefit of the public.

The Academy comprises the UK's most eminent engineers of all disciplines. It is able to take advantage of their wealth of knowledge and experience which, with the interdisciplinary character of the membership, provides a unique source with which to meet the objectives.

Its activities include an extensive education programme, research chairs and fellowships, visiting professorships, industrial secondments and international travel grants. It provides expert advice on engineering matters to government and other bodies, and administers the UK's premier annual prize for innovation in engineering, The Royal Academy of Engineering MacRobert Award.

The Academy was founded in 1976 as The Fellowship of Engineering on the initiative of HRH The Duke of Edinburgh and a group of distinguished engineers. It was granted its Royal Charter in 1983 and, with the consent of HM The Queen, adopted the present title in 1992.

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James Armstrong is a member of several professional bodies, and Past President of the Institution of Structural Engineers. He has played an active role in monitoring and developing educational policies in professional education, he acts as coordinator for the work of The Royal Academy of Engineering Visiting Professors in Principles of Engineering Design and chaired the Academy committee considering design matters in engineering from 1993 to 2001.

He has been a visiting professor and lecturer at several universities in the UK and also in the US, South Africa, Australia and New Zealand. He has lectured widely in these countries and elsewhere – notably in Brazil, Russia, Sri Lanka, Singapore, Hong Kong and Nepal.

His career has been predominately as a consulting engineer. He retired in 1989 as a partner in the Building Design Partnership, where he was responsible for planning and designing such major projects as the Channel Tunnel Terminal works, the Falkland Islands Airport, and the University of Surrey.

In 1996/7 he redrafted the Code of Practice for the Institution of Civil Engineers, and co-authored a book on engineering ethics, published in 1999. He is particularly interested in the development of design abilities, in multidisciplinary design-team projects, and in the philosophy of professional practice. He was awarded the OBE in 1996 for services to education and to engineering.

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Images kindly supplied by Chas A. Blatchford & Sons,
Mott MacDonald, IVAX Pharmaceuticals and Rolls-Royce