as the National Ignition Facility and the proposed European HiPER project (see ‘Generating Laser Energy’, Ingenia 33) will make significant steps towards realising this potential energy source. A fundamental requirement to enable inertial fusion energy is large scale ultra-precision optics. Clearly, large high-power laser focusing lenses and mirrors have additional requirements to those used for telescope. High energy beams will eventually start to degrade the surfaces and thus reduce the reflectivity and the life of mirror and lens components. This surface degradation makes ultra-precision surfaces major ‘wear’ components within inertial fusion programmes. The optics employed in inertial fusion programmes today rely on large scale telescope-derived technologies; segmented mirror technologies being a clear example.

The engineering achievements necessary to develop a nuclear fusion power station, one based on laser containment and ignition, represent an engineering challenge as significant as the space programmes of the 1960s. Some of the most challenging aspects of fusion energy programmes are related to ultra precision manufacturing capability.

**THINKING AHEAD**

It is important to reflect on the fact that basic science programmes, such as astronomy, set extreme engineering specifications which can be considered ‘stretched goals’. In satisfying these ‘stretched goals’ techniques emerge that later become the core technologies of advanced manufacturing businesses. And importantly for the engineering profession these goals represent exciting and rewarding challenges for our next generation of engineers.

**FIVE MIRRORS ENSURE CLARITY**

When it goes into operation in 2017 the European Extremely Large Telescope (E-ELT) will be the largest ground-based telescope in the world and will be over 100 times more sensitive than existing counterparts thanks to a revolutionary design involving the use of five different mirrors. The primary 42m diameter mirror will be composed of ~1,000 hexagonal segments, each 1.4m in size. Each mirror segment has a form accuracy specification of 25nm (1 millionth of an inch). The secondary mirror will be 6m in diameter in order to overcome the fuzziness of stellar images caused by atmospheric turbulence the telescope will also need to incorporate adaptive optics in its system. A tertiary mirror, 4.2m in diameter, will relay the light to the adaptive optics system, which will be composed of two further mirrors – one with a diameter of 2.5m supported by 5,000 or more actuators that will be able to distort its own shape a thousand times per second and one with a diameter of 2.7m that will allow for final image corrections. This five mirror approach will produce exceptional image quality, with no significant aberrations in the field of view.

The total rotating mass of the telescope will be 5,500 tonnes. Two platforms on each side of the structure will each hold a number of large instruments so that they can be quickly put on line.

The reference design for the mirror was signed off at the end of 2006 and the project has now moved on to the establishment of a number of industrial and instrument studies to establish the feasibility of the concepts involved – though details are for the most part still confidential. The site where the telescope will be located is due for announcement this year with construction scheduled to get underway in 2010.

**BIOGRAPHY – Professor Paul Shore**

Professor Paul Shore is the Head of the Cranfield University Precision Engineering Centre and McKeown Professor of Ultra Precision Technologies. He is also the Director of the UK’s Integrated Knowledge Centre for Ultra Precision and Structured Surfaces in North Wales. It houses industrial scale facilities for rapid production of large scale ultra precision and structured surfaces.

**ON BEING AN ENGINEER**

On May 15 2008, the Lord Browne of Madingley presented the Lubbock Lecture, marking the centenary of the founding of Engineering Science at Oxford. In the lecture, on which this article is based, the President of The Royal Academy of Engineering spoke on what it is to be an engineer. Drawing on his own experiences at BP, he put forward the view that a successful engineer requires not only technical know-how but also an awareness of the political, social and business concerns central to any significant engineering challenge.

I want to demonstrate that engineering is at the centre of society – that engineers have a unique set of skills and perspectives which should be used to create a better future for all of us. In order to do that, I would like to talk about a major engineering project that I was involved with and then about the challenges facing young engineers now and the skills that they need to meet them.

**VARIED SKILLSETS**

The bedrock of engineering will always be the application of mathematical and physical theory to create wealth and to improve our quality of life. But engineering is far more than just applied science. The essence of engineering is in its practice. The particular skills of engineers are developed by solving real world problems rather than becoming conversant in physical theory. The complex nature of these practical engineering challenges means that engineers need to engage with communities, with politics, with economic realities and with environmental considerations. The bigger the engineering challenge, the greater the need for judgement and, just as importantly, empathy.

ENGLAND Eyemouth

Pipeline route crossing the landscape, Turkey, June 2004 © BP plc

FABRICATION AND USES OF ULTRA-PRECISION SURFACES WEALTH CREATION
In order to demonstrate these points, I’m going to describe a major engineering project from my own experience as CEO of BP. This is the story of the Baku-Tbilisi-Ceyhan pipeline. The BTC pipeline, as it is called, was an enormous undertaking from a technical perspective. But the success of this project was predicated on the ability of the engineers to manage a host of social, economic, political and environmental issues.

**TECHNICAL CHALLENGES**

The oil reserves of the Caspian Sea have been known about for a long time. By 1900 there were more than 3,000 oil wells in Baku, the capital of Azerbaijan. As the Caspian is an inland sea, transporting the crude oil from there to world markets has been a longstanding challenge. The BTC project met that challenge by building a pipeline of more than 1,000 miles in length. The pipeline runs from a modern offshore platform in the Caspian Sea, through Azerbaijan and Georgia, reaching a terminal on the Mediterranean coast of Turkey. The oil completes its journey end-to-end in just 10 days, flowing at a rate of one million barrels a day. The first oil reached its destination in May 2006.

The technical challenges in designing and building the pipeline were immense, not least because of the sheer scale of the project. The BTC is the second longest oil pipeline in the world and it cost over US$4 billion to build. The pipeline climbs severe gradients, up to 3,000 metres in places. It crosses 1,500 rivers and roads and is buried along its entire route. The construction of the pipeline was complicated by the fact that it was only possible to work during certain months of the year because of inclement weather.

Of course the all-important consideration in the construction of any pipeline is its route. Looking at gradient, waterways, roads and other communication networks is a routine task for an engineer constructing a pipeline of this size. But if these factors alone were taken into consideration, the pipeline would have taken a very different route to that which it eventually followed.

**POLITICAL OBSTACLES**

In seeking the best route, BP's engineers had major political obstacles to contend with. Azerbaijan is flanked on one side by Armenia. The relationship between these two countries has for several decades been hostile, dating back to the Armenian-Azerbaijani conflict which broke out during the final years of the Soviet Union. In the 1990s, when plans were being laid for the pipeline, the situation between the two countries was far from stable. I experienced this first-hand during one of my visits, which coincided with Armenia invading Azerbaijan. It was clear that laying the pipeline between these two countries would entail too much political risk. Azerbaijan's other neighbour on the shores of the Caspian is Iran. Political relations between Iran and the US were tense and the number of US companies involved in the BTC partnership ruled out laying the pipe in that direction too. So the route out of Azerbaijan had to be through Georgia. The Georgian authorities were willing to do business with us, but the then President, Eduard Shevardnadze, placed many restrictions on project, making it plain that technical considerations were not his main concern. The planning of the pipeline route was thus fraught with political obstacles that had a fundamental impact on the engineering of the line.

**ENVIRONMENTAL RISKS**

And business risks were by no means the greatest of the risks to be managed. The very fact this was an oil pipeline meant the project involved inherent environmental risks. There was a constant risk of a leak or spill that could devastate the natural environment – in the midst of some extraordinarily attractive scenery. It is of paramount concern to the engineer that environmental risks are kept as low as reasonably possible and that, should accidents happen, the consequences can be controlled.

In this case, the risk was heightened by the route that we were forced to take. The pipeline crossed several seismic
ON BEING AN ENGINEER

Sir Harold Hartley in 1964, first lecture commemorating the Hon Maurice Fox Pitt Lubbock. The lecture is intended for scientific and lay audiences, and is on engineering in relation to its environment – its industrial application, its place in society, its significance for managers, sociologists, economists and others, and its significance for education. The lecture was given by Sir Harold Hartley in 1964.

Pipeline construction on severe gradients, Georgia, August 2004.

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Pipeline construction on severe gradients, Georgia, August 2004.

The BTC project set particularly impressive standards in this area. Some 450 communities and approximately 750,000 people were affected by the construction of the pipeline. But it was our aim that no person would be displaced. And we were successful in meeting this aim – no person had to leave their home as a result of the project. Landowners were able to return to their land and to use it as before with only minimal disruption.

Social Challenges

As well as technical, political and environmental challenges there were also great social challenges. The BTC project set particularly impressive standards in this area. Some 450 communities and approximately 750,000 people were affected by the construction of the pipeline. But it was our aim that no person would be displaced. And we were successful in meeting this aim – no person had to leave their home as a result of the project. Landowners were able to return to their land and to use it as before with only minimal disruption.

That is no small feat, considering we had to deal with 1,000 landowners, owning 30,000 parcels of land in three different countries. The land had to be procured ethically, through a fair and transparent system of compensation. Construction couldn't take place without agreements on land, and therefore settling and paying compensation had to be factored into the project schedule. Land procurement was a rate determining step for the entire project.

The positive social impacts of the pipeline were considerable. At peak levels, 22,000 people were employed, between 70% and 80% of whom were local people and all of whom received training and education as well as wages.

So, technical, political, environmental and social complexities were an inherent part of the engineering challenge.

Interdisciplinary Skills

Of course no engineer can be expert enough to deal with these issues on her or his own. An essential engineering skill is being able to recognise the limits of one's competences and to procure expertise where necessary, working with people from different sciences and cultures. The BTC project drew on a wide range of experts: specialists in biodiversity, who alerted us to threats to wildlife, NGOs and human rights organisations, who scrutinised and advised us on environmental and social impacts; and archaeologists, who helped us navigate around historical sites along the route.

These groups were by no means passive observers. There were inevitably objections and debates. A project of this level of complexity and political sensitivity will never leave everyone happy. But it is a central feature of engineering projects that choices involve tradeoffs. Engineers must work in imperfect circumstances with competing demands. All of this demonstrates that engineers must be able face in many different directions. Engineering is not just understanding and applying scientific theory. I believe it's time to redefine the package that makes up the term 'engineering skills'.

We must all work to ensure that the public – especially young people – understand the dynamic role of the professional engineer in making a difference and shaping the future of society. And engineering students need to be alert to the broader impacts of what they do.

We must teach our engineers to understand the workings of the worlds of business, politics and public policy. We must prepare students for real world problems in all their complexity. I firmly believe that opening minds to wider issues will help engineering departments, like ours, to help attract the very best students. Opening engineers' minds to these wider issues will also be of benefit to society.

Engineering the Future

To a great extent the need for oil results from our reliance on the motor car. However, events might have developed differently. The BTC pipeline might never have been needed. It was a hundred years ago that Oxford University began teaching engineering science. It was also one hundred years ago that the Model T Ford went into mass production. When the Model T was created, it could have run on either gasoline or ethanol. Gasoline prevailed because of 'Prohibition' in the United States, which restricted the production of alcohols, and because of the low price of oil.

The impacts of that development have been as significant as the advent of the motor car itself. Gasoline is a high-carbon fuel. Burning it releases greenhouse gases, the consequences of which we are only now beginning to understand. Gasoline’s predominance, the reasons for which had little to do with pure engineering, has had profound impact on engineering. The BTC pipeline example shows that engineers can have an equally profound impact on politics and economics.

Engineers cannot predict the future. But we can use our expertise to have a positive influence on that future.

Lord Browne of Madingley, FIBS.