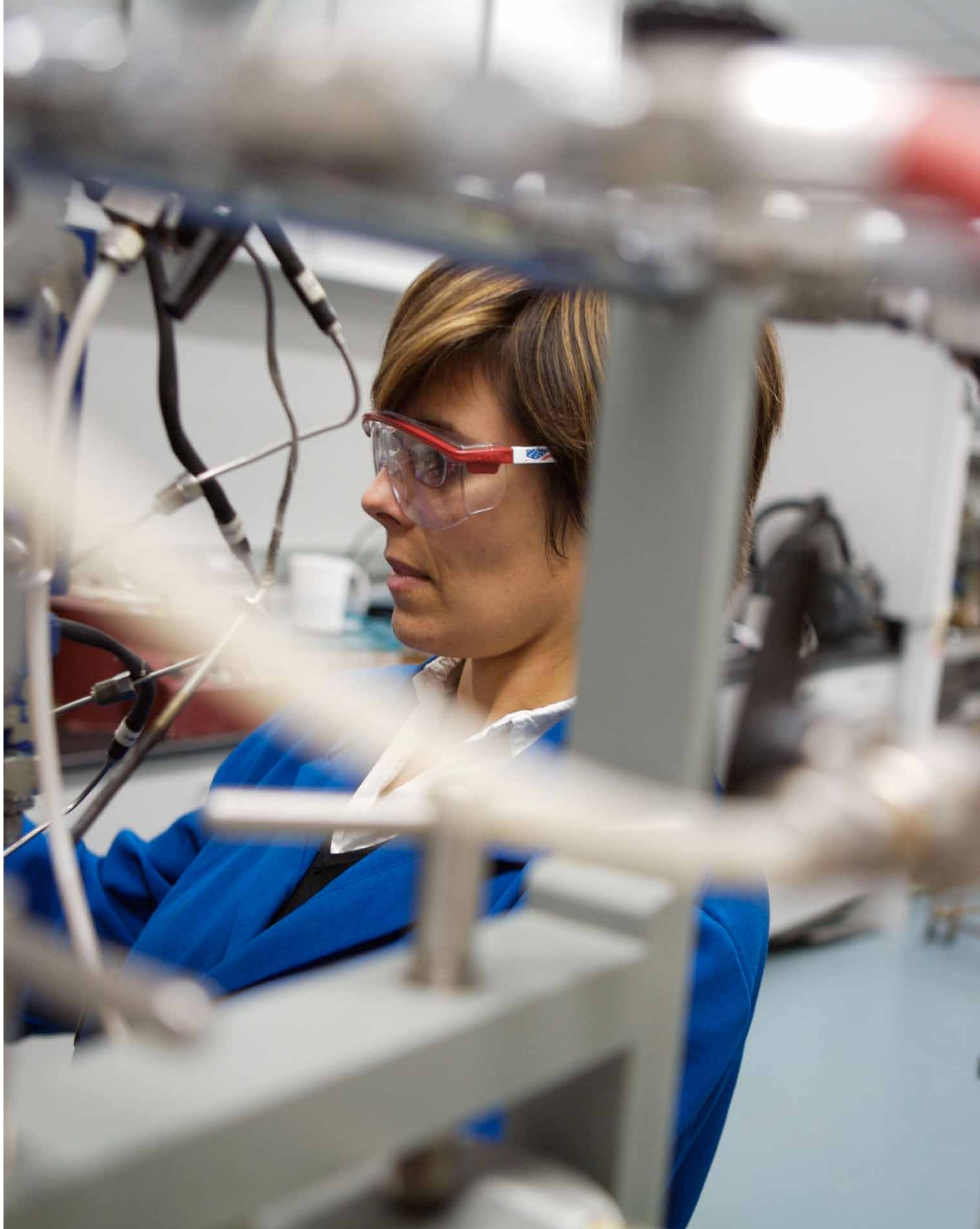
ENHANCED OIL RECOVERY

Musallim Gathering Station Enhanced Oil Recovery, Oman

READY FOR THE CHALLENGE
IMPROVED OIL RECOVERY – ADVANCED WATERFLOODING
ENHANCED OIL RECOVERY – CHEMICAL TECHNIQUES
ENHANCED OIL RECOVERY – MISCIBLE GAS FLOODING
ENHANCED OIL RECOVERY USING HEAT
OUTLOOK

A 1% increase in the global efficiency of hydrocarbon recovery could deliver three years of annual production at today's level

Core samples, Shell Technology Centre Rijswijk, the Netherlands



Shell Technology Centre Westhollow, Houston, USA

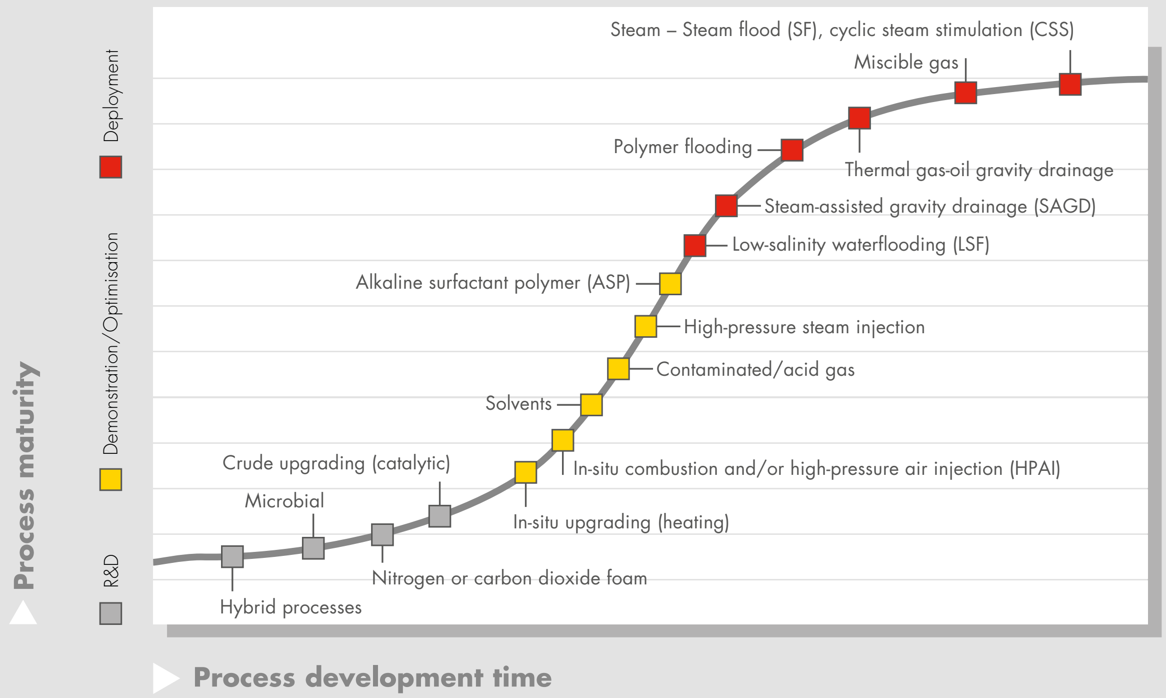
Ready for the challenge

Global energy demand in 2050 could double or even triple from its 2000 level, assuming the emerging economies follow established growth patterns. The contribution to supply made by renewable forms of energy is growing steadily and could reach 30% by 2050. This, however, leaves a huge balance to be met, so oil and gas will remain an indispensable part of the global energy mix for decades. At the same time, existing oil fields are maturing and the task of finding and recovering new reserves becomes more challenging. Consequently, providing these much needed hydrocarbons poses a challenge that requires effective and innovative responses.

Construction at the Qarn Alam EOR project, Oman

Mature fields worldwide account for a large proportion of the global oil supply. Therefore effective strategies to maximise the amount of oil we can recover from them are vital to future supply. Shell is rising to the challenge in numerous ways. We are continually searching for innovative ways of finding, developing and producing hydrocarbons that are efficient and cost-effective and minimise harm to the environment.

Choosing the best recovery technique requires deep understanding of reservoir behaviour and oilfield economics



Shell's technology programme includes various initiatives at different stages of maturity. Basic research is ongoing in areas such as in situ combustion and the use of solvents; we are working with our venture partners on pilot trials and demonstration projects in Russia, Malaysia and the Middle East; and we are conducting full-scale projects in some of our mature assets across the world

IN PURSUIT OF THE PRIZE

Striving to increase the amount of oil we recover from existing fields makes great sense. The prize is substantial: roughly two-thirds of the oil in conventional reservoirs around the world is left behind. Studies indicate that just a 1% increase in the global efficiency of hydrocarbon recovery would raise conventional oil reserves by up to 88 billion barrels, which is equivalent to three years of annual production at today's level.
Shell is one of the leaders in the race to increase the amount of oil recovered from existing fields. A large overall research and development expenditure, more than $1 billion in 2010 and the highest of all the international oil companies, underpins our efforts in this area.

Spiral CT technology in combination with core flooding, Shell Technology Centre Rijswijk, the Netherlands

With oilfields maturing worldwide, Shell remains deeply committed to EOR and to continuously pushing the envelope of technology innovation in this critical area. Shell and its venture partners have some 10 projects to enhance recovery from existing fields at the development stage or in operation, and more than 25 field trials or studies under way.

ENERGISING OIL IN THE RESERVOIR

Oil recovery is a complex business demanding deep technical know-how and extensive operational experience for maximising recovery and delivering profitable and environmentally responsible projects.

There are many ways of getting oil out of the ground. Normally, primary and secondary recovery processes can extract 30–35% of the oil in a reservoir. During the primary recovery phase, the natural reservoir pressure forces oil into the wellbore. Thereafter, during the secondary or improved oil recovery (IOR) phase, waterflooding or gas injection is used to boost declining pressure and sweep the oil from the reservoir.

Tertiary recovery or EOR, which may actually be used at any point in the life of a field (even from the beginning in some reservoirs), relies on the reduction of surface tension or viscosity to encourage the flow of oil trapped in the rock. This is achieved by injecting chemicals (polymers or surfactants), gases (carbon dioxide, hydrocarbons or nitrogen) or steam into the reservoir. EOR may help to extract a further 5–20% of the oil in place. Depending on the reservoir, total recovery levels up to 50–70%. Occasionally even higher levels are achievable.

IOR and EOR technologies are highly complementary. Ultimately, it is all about optimising recovery and about energising the oil in the reservoir to drive more of it to the surface.

TECHNOLOGY TAILORED TO THE RESERVOIR

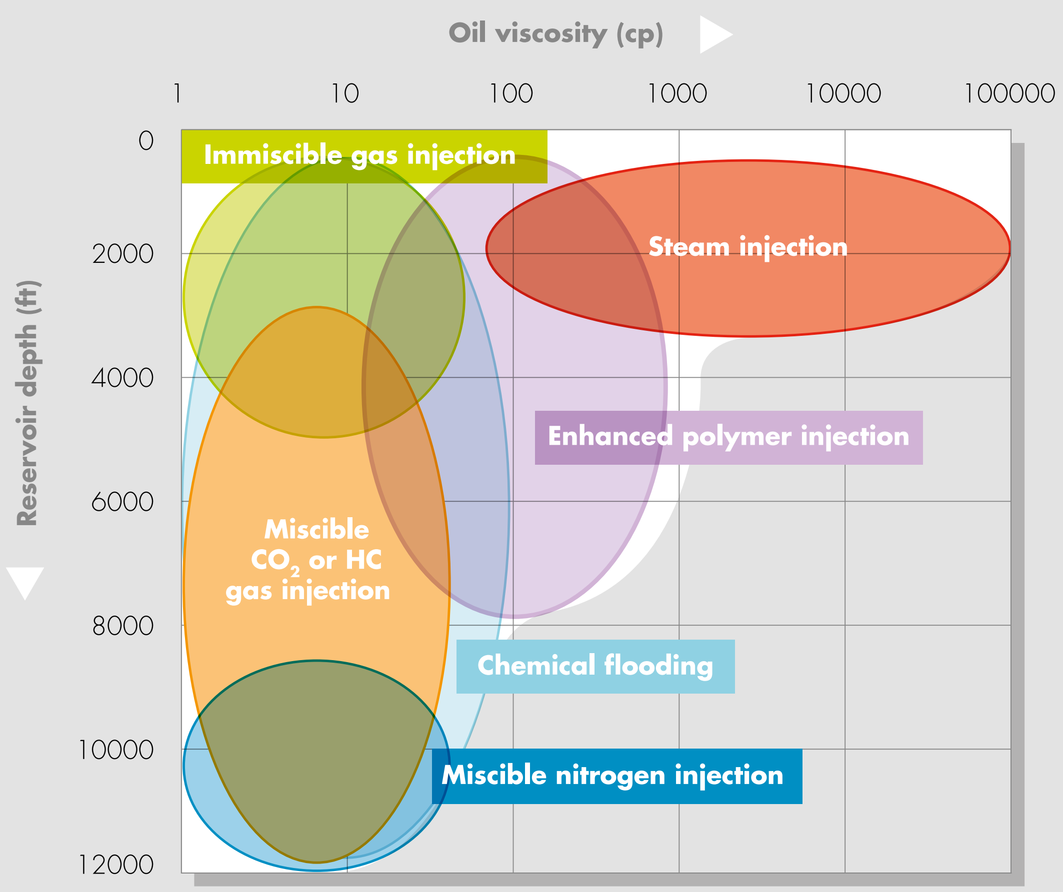
Shell has a strong track record of applying IOR and EOR with successful projects in waterflooding, miscible gas injection and thermal and chemical EOR. We are pursuing a concerted oil recovery technology programme in our world-class research centres in the Netherlands, the USA, Canada and Oman, all of which enjoy strong links with leading local universities. We are working to improve existing technology and to find innovative ways of applying it; we are examining entirely new techniques to energise reservoirs; and we are developing partnerships and alliances to help deliver these technologies in the field. We have devoted considerable effort to developing better waterflooding processes. Low-salinity waterflooding (LSF), which is described later, is one important outcome of this work.

WORLD-BEATING TECHNOLOGY PLUS VAST OPERATIONAL EXPERIENCE GAINED IN COUNTRIES SUCH AS OMAN GIVE SHELL THE ABILITY TO DEVISE INNOVATIVE RECOVERY SOLUTIONS AND TO DEPLOY THEM

Shell’s track record in this area can be attributed to an integrated approach and a combination of features:

- a deep commitment to research and development across a wide technology spectrum;
- a deeply ingrained culture of innovation and leading global talent;
- a fully integrated approach to technology, backed up by a dedicated global technology organisation;
- technology partnerships in the commercial and academic arenas as integrated parts of Shell strategy; and
- global operational experience and proven project execution skills.

Robot for high throughput chemical EOR research, Shell Technology Centre Rijswijk, the Netherlands



EOR encompasses a range of technologies, each of which is suitable for application at different reservoir depths and for oil with differing properties. Choosing the best recovery technique requires deep understanding of reservoir behaviour and oilfield economics. Shell has high-viscosity fields in North America and the Middle East that benefit from the injection of steam to thin the oil or polymers to thicken the water and improve the sweep. We also operate lighter oilfields where, with increasing depth, and hence pressure and temperature, carbon dioxide and other gases become miscible with the oil and reduce the residual oil saturation in the reservoir. This chart shows which processes might be viable in a given reservoir.

Advances in oilfield technology are leading to step changes in oil recovery

INNOVATIVE SURFACTANTS THAT PROVIDE BEST VALUE RECOVERY

The surfactants used for chemical EOR form micro-emulsions by breaking down the interfacial tension between the oil and the water in the reservoir rock. Each EOR application is different. Consequently, the composition of the surfactant mixture needs tailoring to a given specific environment: the properties of the oil and the rock, the salinity of the water and the reservoir temperature, pressure, permeability and porosity. Inevitably, a balance has to be struck between the cost of the surfactants and the increase in recovery. Research at Shell's Westhollow Technology Centre, in Houston, USA, and the Shell Technology Center Amsterdam, the Netherlands, aims to produce surfactants that provide the best-value recovery from a field. The idea is to use these to replace some of the surfactants normally applied to optimise the overall economic performance of an EOR scheme. The work is at an early stage, but, if successful, the technology could enable operators to produce more oil from mature assets or even to turn previously abandoned fields back into production.

Our research includes several exciting new developments that take us beyond the traditional boundaries of EOR techniques. For example, we are looking at chemical polymers that function effectively in high-salinity, high-temperature environments; one objective is to be able to enhance recovery from the most challenging oilfields. We are examining the idea of using solvents to dissolve heavy oil or dilute lighter oil; the advantage of solvents is that, they can be used to enhance waterflood and gas and steam injection schemes. What's more, they are recyclable. And we are seeking to improve the effectiveness of gas injection schemes by adding surfactants. These produce gas foams within the reservoir that form a more even displacement front and reduce the likelihood of gas breakthrough.

Our goal is to maximise the value of the assets that we operate or have a partnership interest in. This means extracting more oil from a broad variety of reservoirs while simultaneously reducing unit costs and energy use, maintaining high safety standards and minimising our environmental footprint.

PROGRESS RELIES ON PARTNERSHIP

Sharing our knowledge, experience, skills and resources is vital to making the rapid progress necessary in key areas such as EOR. For this reason, Shell is a firm supporter of technology partnerships.

A classic example is the work we are doing at Shell Technology Oman in conjunction with Petroleum Development Oman (PDO)[1] Under an EOR Strategic Alliance, this provides support for a series of EOR projects in the country. Projects already under way with PDO involve steam injection in the Qarn Alam, Fahud and Amal fields, polymer injection in the Marmul field and miscible gas injection at the Harweel field cluster. The alliance is targeting the next wave of EOR technology innovation and recovery.

Reservoir surveillance technology is also playing a vital role in optimising the performance of these EOR schemes. We have made particularly significant advances in geomechanical modelling and monitoring techniques such as deformation-related, microseismic fracture monitoring and control management tools, and leading-edge, time-lapse, seismic flood-front monitoring and control techniques. In collaboration with oilfield services and other companies, new generations of subsurface characterisation and in-well and areal surveillance technologies are under development.

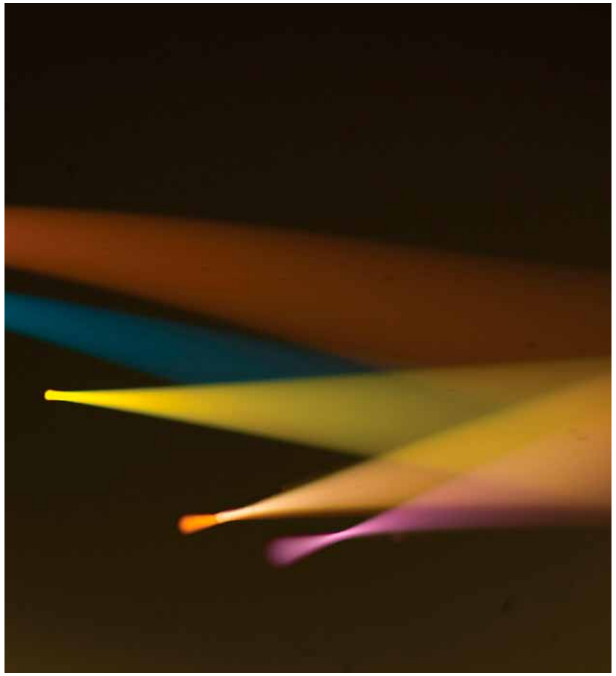
For the steam injection projects, one of the main aims is to minimise the amount of natural gas used to create the necessary steam. At Qarn Alam and Amal fields, 80% of the steam

[1] PDO is a joint venture between the Omani government, Shell and other partners.

Amal fields, Oman

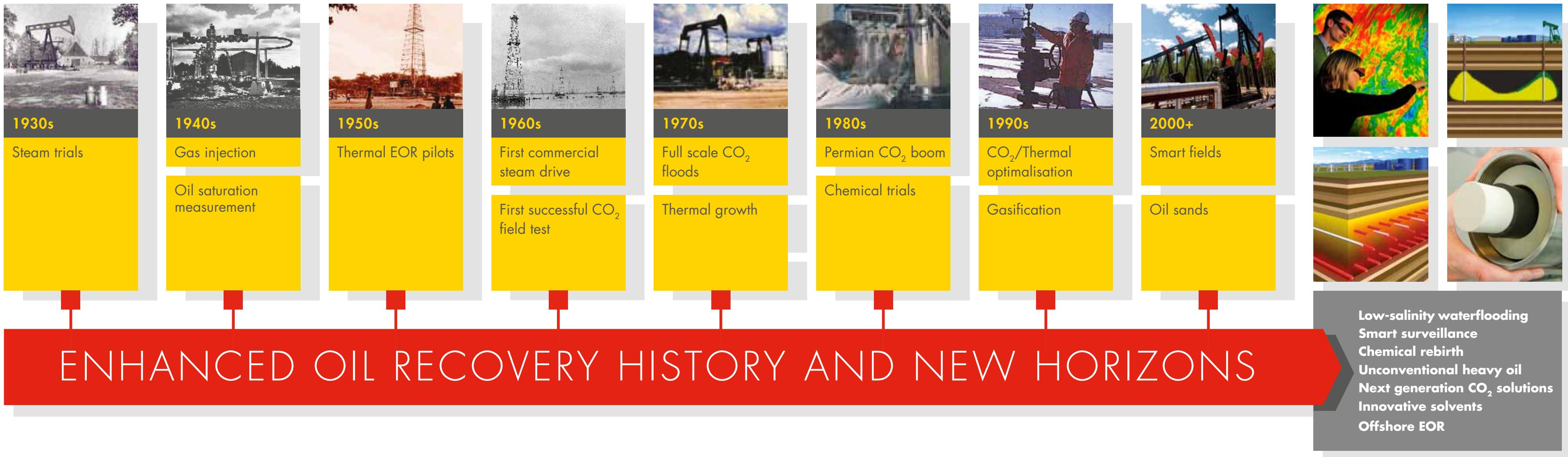
INTEGRATION IS THE KEY TO PROGRESS IN EOR. RESERVOIR SURVEILLANCE IS A GOOD EXAMPLE OF AN AREA WHERE ADVANCES HAVE BEEN MADE ON THE BACK OF OUTSTANDING INPUT FROM A RANGE OF DISCIPLINES

Successful EOR projects rely on understanding and being able to monitor changes in the reservoir when it is heated or flooded with chemicals or miscible gas. Shell has made serious progress in this area as a result of its ability to combine input from a range of different scientific and engineering disciplines, not least, geology, geophysics and electronics.
We are also working with various technology partners from in and outside our industry, and taking an integrated approach to developing new surveillance capabilities based on leading-edge research into fracture monitoring and control, fibre-optics and time-lapse seismic flood-front monitoring. Our work on fibre optics is proving particularly valuable; distributed temperature, pressure, acoustic and strain measurements around the wellbore are now possible.



Fibre optic for advanced reservoir modeling

Technology integration is vital to continuously achieving higher recovery factors



needed for the projects is generated from waste heat captured from local power stations. Steam generation using solar energy is also being evaluated and plans are being made to trial this concept at Amal field.

In another example of effective technology partnership, Shell is working with the Technical University of Delft, the Netherlands. We are looking at the application of advanced oilfield measurement and control techniques, and are also setting up what we have termed a *recovery factory* for EOR technology developments. The joint programme has already resulted in promising new sensors to detect chemical components downhole. These can be used with advanced computer models to optimise production. Work that combines inputs from several diverse data sources to further improve our understanding of oil recovery mechanisms is also showing promise. One highlight of this work is using innovative satellite-borne sensors to measure minute deformations of the Earth's surface caused by changes in the underlying reservoir.

HIGHER RECOVERY THROUGH TECHNOLOGY INTEGRATION

Projects to unlock the full value of mature assets require sound knowledge of the relevant recovery technology and much operational experience. Shell possesses both of these, but they are not enough on their own. Technology integration is just as vital to achieving higher recovery factors.

Shell's success in EOR is based on bringing to the table the subsurface and surface capabilities that surround the basic recovery process: capabilities in reservoir characterisation flood-front monitoring, interpretation, modelling and management; field development planning; and wells and facilities management.

These are table stakes however. It is also essential that we understand what is different about EOR and can, therefore, predict how chemicals, steam or gases injected into the reservoir will migrate and behave. We also have to be able to monitor the movement of fluids towards the wellbore and to optimise operations. Reservoir modelling skills to help understand the complex displacement processes that occur throughout a field are at a premium here. The differentiator will be how well the various technology and capability aspects are integrated to form a tailored solution for each field. Shell has a series of proprietary technologies that contribute to raising oil recovery. Among many good examples are Smart Fields® technology and the FieldWare® Production Universe® software suite. Underpinning capabilities such as our lean process-based business model, which is designed to simplify and streamline operational workflows, have also proved valuable, for instance, in improving well and reservoir management programmes. Aera Energy LLC's thermal EOR projects in the USA and the steam injection project in Schoonebeek field, which is operated by the Shell and ExxonMobil joint venture Nederlandse Aardolie Maatschappij (NAM), in the Netherlands are both good examples of application in our joint ventures.

SMART FIELDS TECHNOLOGY BOOSTS PRODUCTION IN RUSSIA

Salym Petroleum Development (SPD) has equipped well pads in the Salym fields in Russia with Shell Smart Fields technology. This enables the operator to monitor, remotely and in real time, the levels of produced oil and injection water. This has had two immediate practical consequences: there have been fewer breakdowns of well equipment and the run lives of electrical submersible pumps is longer. Together, these have reduced production downtime.

Perhaps more importantly, SPD is better able to optimise its production operations throughout the fields. The overall result is a 2–2.5% increase against planned production to date achieved, not through the application of any specific EOR technology, but through "smart" field management.

Salym Petroleum Development, Russia

The Ursa–Princess waterflood scheme constitutes one of the largest IOR projects ever undertaken on an existing platform in the Gulf of Mexico


Ursa Tension Leg Platform, Gulf of Mexico, USA

Improved oil recovery – advanced waterflooding

Success in waterflooding is a key stepping stone to the success of EOR. Waterflooding combines geoscience and oilfield engineering. There is an art to waterflooding, especially when it comes to predicting precisely how water will flow through a given reservoir, which is actually the key to increased recovery and a successful project.

Though a long-established technique, waterflooding still poses considerable practical challenges and still offers significant rewards for those willing to tackle the subject in new and imaginative ways. Shell is using all its knowledge and operational experience to raise the art of waterflooding to the next level, to unleash its untapped potential. EOR is often applied to drive recovery further.

Sulphate Removal Unit Ursa, Gulf of Mexico, USA

BENEFITS AND CHALLENGES

Waterflooding is widely used to boost declining reservoir pressure and sweep additional oil into producing wells. It has the advantage of low capital and operating costs, certainly when compared with most EOR techniques, though the cost of drilling any new injection wells has be taken into account.

One of the challenges of waterflooding, especially when used offshore, is the size of the treatment plant needed to remove oxygen and sulphate contaminants from the water; a measure for avoiding corrosion, reservoir souring and aerobic bacterial problems.

With low-salinity waterflooding technology it is possible to adjust the salinity and ionic composition of the injection water to suit a specific reservoir formation

EOR trial, Brunei

Low-salinity waterflooding field test, Middle East

GULF OF MEXICO FIELD LIFE EXTENDED BY A DECADE

Production from Shell's Ursa field in the Gulf of Mexico began in 1999. Four years later, oil from the nearby Princess field was added to the Ursa production stream, and field studies began on evaluating how recovery could be boosted further. The aim of the Ursa-Princess waterflooding project was to maintain reservoir pressure and prolong the lives of the combined fields. The key challenges were to fit the waterflooding equipment into a limited space on the Ursa tension-leg platform and to minimise the number of new wells required.

After a detailed assessment, Shell engineers decided to treat the water on the Ursa platform to remove the sulphates that might cause reservoir souring. The treated water is fed through twin flowlines to three injection sites: two are existing wells close to the tension-leg platform and the third is a new well some distance to the northeast. Production has been boosted from three Princess wells and up to six Ursa wells.
The Ursa-Princess waterflooding scheme is one of the largest projects ever undertaken on an existing platform in the Gulf of Mexico. It came on-stream in 2008, has a volume enhancement capacity of 30,000 barrels of oil equivalent per day and is expected to extend the lives of the two fields by 10 years. High volumes of construction, maintenance, commissioning and well service work were all undertaken simultaneously and achieved an exemplary safety record.

RAISING RECOVERY TO THE NEXT LEVEL – LOW-SALINITY WATERFLOODING

It is recognised in our industry that waterflooding efficiency can be markedly improved by lowering the salinity of the injected water. The less salt there is in the water, the easier it is to dislodge the oil from the pores in the reservoir rock. With this in mind, Shell scientists are advancing the concept of low-salinity waterflooding (LSF).

Water treatment for LSF typically involves a two-step process of nanofiltration and seawater reverse osmosis. Nanofiltration reduces the hardness of the water by removing sulphates and other divalent ions. This lessens the likelihood of membrane blockages during the subsequent reverse osmosis process to remove the salt from the water. Crucially, with LSF it is possible to adjust the salinity and ionic composition of the injection water to suit a specific reservoir formation and to take into account, for example, the tendency for the clays to swell and for the reservoir to sour. Essentially, Shell is pursuing an innovative way of raising oil recovery rates by matching the properties of the injected water with the characteristics of the rock, the oil and the water in the reservoir to reduce the tendency of the oil to stick to the walls of the pores in the rock.

Recently, various LSF trials have been held in fields in the Middle East. The tremendous potential of the technology is demonstrated by an observed reduction in the residual oil saturation around the wellbore. With our joint-venture partners, we are working to further develop and scale up the technology.

St. Joseph oilfield, Malaysia

GREAT POTENTIAL FOR OFFSHORE EOR

low-salinity waterflooding (LSF) is likely to prove extremely valuable when used for schemes offshore. Seawater reverse osmosis desalination equipment is very light and compact, which makes installation easy in small spaces where conventional steam-driven desalination plants would normally be unsuitable. LSF can also be used in combination with a range of chemical and thermal EOR techniques. Replacing seawater with low-salinity water in polymer flooding, for example, could reduce polymer consumption by between 5 and 10 times. This would result in significant cost savings and lower storage space requirements on offshore installations in addition to the potential recovery benefits of LSF itself. Shell, with its partners, is seeking to apply this technology to raise production levels from fields in the North Sea, the Gulf of Mexico and other offshore basins.

The sustainable development of alkaline surfactant polymer (ASP) technology has generated the power to transform EOR economics

Polymer injection, Marmul, Oman

Enhanced oil recovery – chemical techniques

Chemical EOR is a prime focus for Shell. Our strengths in a range of advanced technologies, encompassing both the upstream and downstream sectors of the industry, truly count in this area. Using our chemicals knowledge and expertise, we have launched new polymer and surfactant technologies that promise to open up fields around the world to the possibility of advanced, highly economic EOR schemes.

Polymer injection, Marmul, Oman

SWEEPING EFFICIENCY GAINS USING POLYMER FLOODING IN OMAN

One of the first fields discovered in South Oman was Marmul. It came onstream 25 years ago but only 15% of the oil in place has been recovered. A waterflooding scheme was installed to boost recovery; however, the oil is so thick and viscous that, in places, the water flooding the reservoir bypasses it rather than sweeping it towards the wells.

PDO operates Marmul field and decided to attempt to increase production and extend the life of the field by switching from

POLYMER ADVANTAGES

Including polymers in the water used to flood reservoirs increases its viscosity. This reduces the water-to-oil mobility ratio and makes it easier to sweep the oil towards the producing wellbores. Upgrading a straight waterflooding scheme to a polymer flood can typically be relatively cheap, though there is the ongoing cost of the polymers to consider.

Trials of the new ASP technology are demonstrating its huge potential and providing important pointers to its larger-scale application

Polymer injection, Marmul, Oman

straight waterflooding to polymer flooding. The scheme involves treating the water to remove impurities before it is mixed with an advanced polyacrylamide and then injected into the reservoir under very high pressure. Since early 2010, PDO has been injecting about 100,000 barrels per day of polymer solution into the reservoir with exceptional results. The aim is to increase oil production by 8,000 barrels per day and to raise the recovery factor from 15 to over 25%.

At Marmul field polymer is injected above formation parting pressure; consequently, effective monitoring is important to the success of the scheme. For normal waterflooding, this is commonly done by well testing: the results of pressure fall-off, flow-back and step-rate tests are integrated to determine injection effectiveness. It is one of the first times, however, that this monitoring technique has supported a polymer flooding project. The motivation for selecting polymer injection technology in existing fields is the need to increase the stability of the injection front and, thereby, raise production by designing a higher viscosity flood than a conventional water flood. The higher viscosity injectant increases the likelihood of conformance challenges, which potentially leads to shortcuts from the injector to the producer wells. With the higher capital cost associated with a polymer flood, the need to manage polymer flooding tightly has become much more urgent. Carefully managed well and reservoir surveillance has proved successful for PDO in supporting the realisation of increased recovery through Shell's leading-edge technologies, including the selection, design, interpretation of appropriate well-test and other novel surveillance options.

Following this success, PDO intends to expand operations at Marmul and so create one of the largest polymer flooding facilities in the world. It is expected to have the capacity to treat some 500,000 barrels per day of water for flooding operations.

SURFACTANT FLOODING – OVERCOMING THE COST CHALLENGE

Waterflooding schemes have to work against the capillary forces in the pores of the reservoir rock that hinder the flow of oil into the wellbore. Lowering the surface tension at the oil/water interface in the rock through the use of surfactants can reduce these forces. Unfortunately, given the pore volumes that have to be treated, large quantities of surfactant are generally necessary to dislodge meaningful amounts of extra oil. More often than not, this makes pure surfactant treatment uneconomic.

A way of overcoming this problem is to inject a less expensive alkali into a formation, where it reacts with the acids in the crude oil to form petroleum soaps or in situ surfactants. It also reduces the tendency of the surfactants to adsorb onto the rock.

This may sound easy, but it is not. A solid understanding of the reservoir chemistry and careful control of the alkali injection are necessary for good results. Shell's response to these various challenges has been the sustained development of alkaline surfactant polymer (ASP) flooding.

ECONOMICS DRIVE ALKALINE SURFACTANT POLYMER FLOODING

Shell introduced ASP during the 1980s in the USA. Early trials in the White Castle field, Louisiana, USA, demonstrated the technology's potential. Over the years, subsequent trials have shown it is possible to recover an additional 10–25% of the oil from a chosen reservoir using ASP. More recently, as the oil price has risen, there has been an upsurge in interest in this exciting technology and yet more innovation. Further demonstration projects are now under way in several oilfields around the world–with Shell as a partner.

ASP involves injecting alkali with small amounts of surfactant into a reservoir. The objective is to achieve optimum chemistry at large injection volumes for minimum cost. The alkali-surfactant mixture forms an emulsion with the oil, which is then swept from the reservoir using a polymer drive.

PDO has carried out ASP field trials in the Marmul, Rima and Lekhwair fields in Oman and has decided to build an ASP pilot plant in Marmul field. Salym Petroleum Development (SPD) has conducted a single-well trial in the West Salym field, in Siberia, Russia. With the remaining oil saturation in the area around the wellbore having fallen to almost zero, the results of this trial were particularly encouraging. Brunei Shell Petroleum has conducted a single-well trial in the Seria field. Here, the focus was on assessing injectivity and the effectiveness of various alkali-surfactant cocktails in different reservoir horizons.

In January 2012, Shell and the Malaysian national oil company, PETRONAS, signed two 30-year production-sharing contracts for EOR projects offshore Sarawak and Sabah. If carried through to fruition, the agreement will bring several key benefits of national importance. It will help build local capabilities in niche EOR technologies. The projected increase in the average recovery factor in the Baram Delta operations and North Sabah fields will be 36–50%, which will add significant value to the upstream industry in Malaysia over the coming decades.

There is enormous potential for innovation in implementing new EOR technologies and through joint research and development efforts to develop new knowledge in chemical EOR that can be applied to other areas in the world.

The ASP technology to be utilised in Malaysia will be the world's first application offshore. And, if the ASP flooding pilot is successful, Shell could be the first organisation in the industry to undertake field-scale offshore chemical EOR, which will be in the St Joseph and other nearby fields.

The agreement provides an opportunity to work with PETRONAS on building local EOR execution, operation, and research and development capabilities.

St. Joseph oilfield, Malaysia

Expanding our understanding of miscible gas flooding using carbon dioxide has resulted in much better EOR technology. In addition, it yields an environmental premium

Enhanced oil recovery – miscible gas flooding

Shell has a deep history and ongoing involvement in miscible gas flooding. The technique offers great potential purely in terms of EOR. In addition, it provides advantages in the management of reservoirs containing sour and contaminated gas. And, not least, there is the environmental premium from reducing carbon dioxide emissions to the atmosphere through carbon dioxide EOR.

Gas injection, Harweel, Oman

Gas injection, Harweel, Oman

FINDING THE RIGHT FIELD

Miscible gas flooding is a particularly effective way of maintaining reservoir pressure and raising oil production rates. The gas essentially acts as a solvent for the oil: the resultant solution has reduced viscosity and hence better flow characteristics. The gases commonly used are methane (sometimes enriched with light hydrocarbons), liquefied petroleum gas, nitrogen and, most significantly, carbon dioxide. The technique is well established, but the challenge is often one of matching an affordable, convenient source of gas with a viable candidate field.

Through carbon capture and storage, and miscible gas EOR, Shell is working hard to bring together two vital areas of technology for the benefit of the wider energy industry and society in general

Gas injection, Harweel, Oman

RAISING PRODUCTION AND CUTTING EMISSIONS

There are two principle motives for using carbon dioxide for miscible gas EOR. First, carbon dioxide is a very effective recovery agent and has a good record of raising oil production levels. Second, it provides the opportunity to reduce climate-change-related carbon dioxide emissions.

There is strong overlap between Shell's research and development programmes in miscible gas EOR and in carbon capture and storage. Many of the important advances we have made in the study of carbon dioxide storage in geological formations can be linked to our work since the 1960s on carbon dioxide miscible gas flooding. Our progress on both fronts has been helped by expertise in a range of related areas: gas separation, subsurface technology, well engineering and reservoir surveillance.

There is a tremendous potential to use the carbon dioxide from non-oilfield sources, notably power generation, in EOR schemes. Shell is working hard to bring together two vital areas of technology for the benefit of the wider energy industry and society in general.

TRACK RECORD IN THE PERMIAN BASIN

Shell has been heavily involved in carbon dioxide miscible flooding for the past 50 years. We implemented one of the world's first commercial schemes in 1972 in the Permian basin North Cross field, USA. This project led to us recovering at least 50% more of the oil in place from the reservoir.

Following this, we developed the world's largest integrated carbon dioxide flooding project in the Wasson field Denver unit, again in the Permian basin. Natural carbon dioxide for this scheme was supplied from the McElmo dome, one of the world's largest-known accumulations of nearly pure carbon dioxide, 800 km away in Colorado. The recovery factors in this landmark project increased by up to 20%. Between 1985 and 2000, approximately 400 million standard cubic feet per day of carbon dioxide was injected into the Denver unit to deliver an extra 120 million barrels of oil. This is more prologue than history though, as Shell exited the Permian basin in 2000 after 30 years of carbon dioxide flooding success. We are taking that experience and know-how to today's opportunities and for integration with carbon capture and storage.

PDO TAKES THE LEAD IN MISCIBLE SOUR GAS FLOODING

Our many years' experience of miscible sour gas flooding are being put to good use in PDO under a sour hydrocarbon collaboration. As one example, the Harweel cluster of fields in Oman contains more than 60 wells drilled into reservoir structures characterised by approximately 100-m-thick carbonate stringers. These slabs of carbonate rock lying at depths of 2.5–5 km are salt encased and contain light sour oil. During the first phase of the project, when production levels were about 18,000 barrels per day, miscible gas containing 3–4% hydrogen sulphide and 10–15% carbon dioxide was injected into the Zalzala field to confirm the viability of miscible sour gas injection.

The comprehensive collection of static and dynamic reservoir data has enabled the evaluation of key parameters such as reservoir compartmentalisation, vertical heterogeneity, lateral continuity, areal sweep and injectant enrichment. The objectives now are to extend the scheme to similar fields.

SCOPE FOR FURTHER RESEARCH IN A REMARKABLY FERTILE AREA

Shell continues to devote effort to improving miscible gas EOR, an area that retains huge potential for oil recovery and carbon dioxide sequestration. Our research focuses on improving the conformance and sweep control of carbon dioxide and other miscible gas floods through, for example, the use of gas foams. We are also working with impure natural gas streams, for example, containing hydrogen sulphide and carbon dioxide. This could open up the development of vast contaminated gas reserves around the world.

Gas injection, Harweel, Oman

Exceptional reservoir understanding, strong commitment and a capacity for innovation move thermal EOR technology forward

Schoonebeek oilfield,
the Netherlands

Enhanced oil recovery using heat

Thermal recovery technology plays a vital role in unlocking the full potential of difficult, heavy oil reserves. Overcoming the challenges surrounding the use of this technique, not least ensuring its energy efficiency, requires robust operating experience, the capacity to deliver large complex projects and a deep commitment to technology innovation.

UNLOCKING THE FULL POTENTIAL

Thermal recovery is commonly used to produce highly viscous oils of less than 20°API. Heat in the form of steam or hot water, or occasionally from in situ combustion, thins the oil and improves the way it flows. The efficiency of the process depends on how much heat is lost to the reservoir rock and how much transfers to the oil.

Though simple in theory, the practice is complicated by the specific properties of the oil and, in particular, the characteristics of the reservoir. In addition, there is the question of the process's energy efficiency and, consequently, the carbon dioxide emissions produced.

Schoonebeek oilfield, the Netherlands

Research at Shell mainly aims for better understanding of the thermal displacement process and finding the most effective and energy-efficient ways of conveying heat into the reservoir using different well architectures. We are also looking at the role of thermal recovery in lighter oil reservoirs. As steam drive and flooding are generally complex processes, surveillance is a critical component of well and reservoir management. In the initial stages of the steam drive process, thorough understanding of the recovery mechanism resulting from the interplay between the steam and the geology is necessary for optimal field management. The major uncertainties in a steam development are generally placing the steam in the appropriate reservoir sections and obtaining uniform areal and vertical steam distribution to drain the complete target reservoir to optimise the critical economic driver of this process, the steam-to-oil ratio. At the

A key advantage of the Thermal-Assisted Gas-Oil Gravity Drainage scheme is the considerable reduction of the number of wells required to heat the reservoir

same time, the steam must remain inside the reservoir. This can be monitored using permanent passive seismic sensors, an area where Shell has proven leading-edge interpretation capabilities.

Shell's time-lapse seismic processing and interpretation capabilities have contributed significantly to the optimal management of steam distribution, along with its surface-deformation interpretation capabilities. Permanent fibre-optic monitoring has contributed to successful placement of a flood inside the reservoir, for which Shell has joint-industry projects and state-of-the-art interpretation capabilities.

DEALING EFFECTIVELY WITH FRACTURED RESERVOIRS

Naturally fractured reservoirs create difficulties for all EOR techniques. Where the production of heavy oil is concerned, these challenges are especially daunting. Over the years, Shell has accumulated considerable expertise in characterising naturally fractured reservoirs. This led to the development of an innovative EOR technique with PDO. Thermal-assisted gas-oil gravity drainage (TAGOGD) was successfully piloted in part of Qarn Alam field in Oman and has since been implemented across the entire field. This is the first time such a scheme has been used in any fractured carbonate reservoir. PDO estimates that the 3–5% recovery factor under cold production will increase to 20–35% with steam TAGOGD.

At Qarn Alam field, the steam is injected directly into the fractures in the reservoir. They act as radiators to heat the rock and reduce the viscosity of the oil by up to 100 times. The thinner oil flows readily from the matrix rock into the fractures and then drains by gravity into an oil rim. A key advantage of the TAGOGD scheme is that the number of wells required to heat the reservoir is considerably lower when compared with conventional steam flooding.

The technique, which was primarily developed to assist the production of heavy oil, is also being trialled in the moderately viscous oil in the densely fractured Fahud field.

EARLY INVOLVEMENT

Shell has been producing bitumen at the Peace River complex in northern Alberta, Canada, since 1979. The oil sands there are estimated to contain several billion barrels of bitumen. The preferred method of production has been cyclic steam stimulation or steam soaking. This involves steam injection into the target zone, followed by a soaking period to heat the reservoir, before oil and water are produced through the same wells. This is repeated several times to establish an extended hot zone, after which the process is converted to continuous steam injection with separate injection and production wells.

The operations in Alberta have taught Shell a great deal about the use of heat to stimulate reservoir production and in particular about reservoir monitoring to optimise thermal recovery processes. Using this experience, and making full use of a range of innovative technologies, Shell has embarked on a programme to significantly expand bitumen production at the Peace River complex.

CONTINUOUS INNOVATION

The South Belridge field in California, which is operated by the Shell joint venture Aera Energy LLC, is one of the five largest onshore oilfields in the USA. It produces 140,000 barrels per day of mostly heavy crude (13°API). The field was discovered in 1911 and has produced over 1 billion barrels of oil. The fact that it has remained so important for so long is largely due to the introduction of steam injection during the 1960s. The field is a perfect candidate for the technique, as the oil is relatively close to the surface and its viscosity falls rapidly when it is heated. Some areas of the field are estimated to have yielded 80% of the oil in place.

Continuous optimisation of the steam flood made possible through advances in steam injection monitoring and control has been absolutely vital to achieving these recovery factors. Local vertical wellbore logging, notably including temperature surveys and neutron logs, provides an overall assessment of steam flood performance and helps to identify bypassed oil. High-resolution 3D seismic surveys have also improved our understanding of the undeveloped parts of the field.

CONSULTING WITH OUR STAKEHOLDERS

The Schoonebeek field was completely abandoned in 1996 and the area was restored to greenfield condition. The redevelopment plan had to ensure the least possible disturbance for the local community and minimum impact on the natural environment. Sound technology selection and rigorous risk management, supported by an extensive and detailed consultation process involving the local people and a variety of stakeholder organisations, achieved this.

This is one illustration of Shell's commitment to sustainable development and safe operation. Health, safety, security and environmental protection are priorities on every Shell project from beginning to end.

The generally higher operational intensity of EOR projects and the associated production complexity put even greater emphasis on these vital issues. Each technology and every individual recovery scheme is minutely assessed in terms of their sustainability and the results are fed into our development plans everywhere in the world.

South Belridge field, California, USA

South Belridge is a perfect example of how continuous technology innovation combined with a rigorous attention to operational efficiency can pay dividends in achieving recovery factors that rank among the highest in the world.

RE-ENERGISING AN IMPORTANT HYDROCARBON ASSET

On its discovery in 1943, the Schoonebeek field in the Netherlands, operated by NAM, a joint venture between Shell and Exxon, was the largest onshore oilfield in Western Europe. However, in 1996, NAM terminated oil production at Schoonebeek because the heavy viscous oil had become increasingly difficult to recover with the techniques and infrastructure available. Only about 25% of its estimated 1 billion barrels of oil had been recovered from about 600 vertical wells.

Schoonebeek oil is viscous and waxy (160 cP, 25°API). Consequently, only about 18% of the total reserves were recovered using conventional techniques. Hot water injection was introduced in 1957, followed by steam injection, which, together, accounted for a further 7% recovery. However, production was eventually undermined by poor economics.

Qarn Alam, Oman

A few years later, growing energy demand and advances in thermal EOR technology led NAM to seek redevelopment options. Following extensive studies and a detailed assessment of various subsurface innovations, NAM and its partner EBN came up with a plan to reopen the western part of the field where previously only 15% of the oil in place had been recovered. The goal is to increase the recovery in the target area and produce an additional 100–120 million barrels of oil in the next 25 years. Peak production is expected to be 20,000 barrels a day.

To increase recovery, the novel technique of gravity-assisted steam flooding (GASF) is used. In GASF, steam is injected through horizontal wells into the reservoir. This mobilises the oil, which drains, along with condensed water, into closely spaced, parallel, horizontal production wells near the base of the reservoir. A steam chamber also develops around the injection well and forces oil towards the production wells. The redevelopment at Schoonebeek involved NAM drilling 73 horizontal wells at 18 well centres.

System integration is a key success factor for Schoonebeek. Relatively pure water is needed for the process and this is supplied from a new waste-water treatment plant in the nearby town of Emmen. There is a steam-raising plant at Schoonebeek, which also generates electricity for the Dutch national grid. The produced oil, water and gas are separated. The oil is then piped to a refinery in Germany; the gas is used to raise steam; and the water is injected into depleted gas fields.

PUSHING THE BOUNDARIES BY RAISING THE TEMPERATURE

Shell continues to push the boundaries of thermal EOR by developing a method of applying downhole heating to heavy oil and bitumen in the reservoir. The aim is to raise the temperature high enough to break the hydrocarbon chains into smaller, lighter molecules. As well as flowing to the surface more easily, these molecules constitute a much higher value product. We are essentially performing in situ upgrading: transporting refinery technology into the reservoir. An extended pilot trial at the Peace River complex has demonstrated the concept, and we are planning further applications of the technology for more difficult oilfields.

There has to be a life-cycle approach to EOR.
The concept of energising the reservoir deserves attention from the earliest stages of field planning and development

Shell Technology Oman, Muscat, Oman

Petroleum Development Oman,
Marmul, Oman

Outlook

Shell remains deeply committed to EOR and to continuously pushing the envelope on technology innovation in this critical area. We firmly believe that advances will continue to stem from the kind of focused, high-quality research undertaken at our technology centres worldwide. At the same time, real progress will require a broad array of oilfield technology skills, the ability to integrate and a willingness to work in partnership with others. These attributes are essential if we are to overcome the challenges presented by reservoirs containing challenging oil.

Solar for EOR

Shell is continuously expanding its global EOR portfolio. PDO is leading the way in EOR implementation, with projects in all three technology families

THERMAL PROJECTS

Fahud SAGOGD
Steam Assisted GOGD in Light Oil or Waterflood or Surfactant

Qarn Alam Steam
Steam in Fractured Carbonates

Habur & Al Ghubar
QA-Type Steam in Fractured Carbonates

Habhab
Thermal field test

Amal E&W & Mukhaizna
Conventional 'Heavy Oil' Steam

MISCIBLE GAS PROJECTS

Al Noor
Miscible Gas or Deep De-Pressurisation

Harweel
Miscible Gas or Nitrogen/CO_2

CHEMICAL PROJECTS

Yibal/Lekhwair
Surfactant/ASP

Nimr & Amin
Polymer

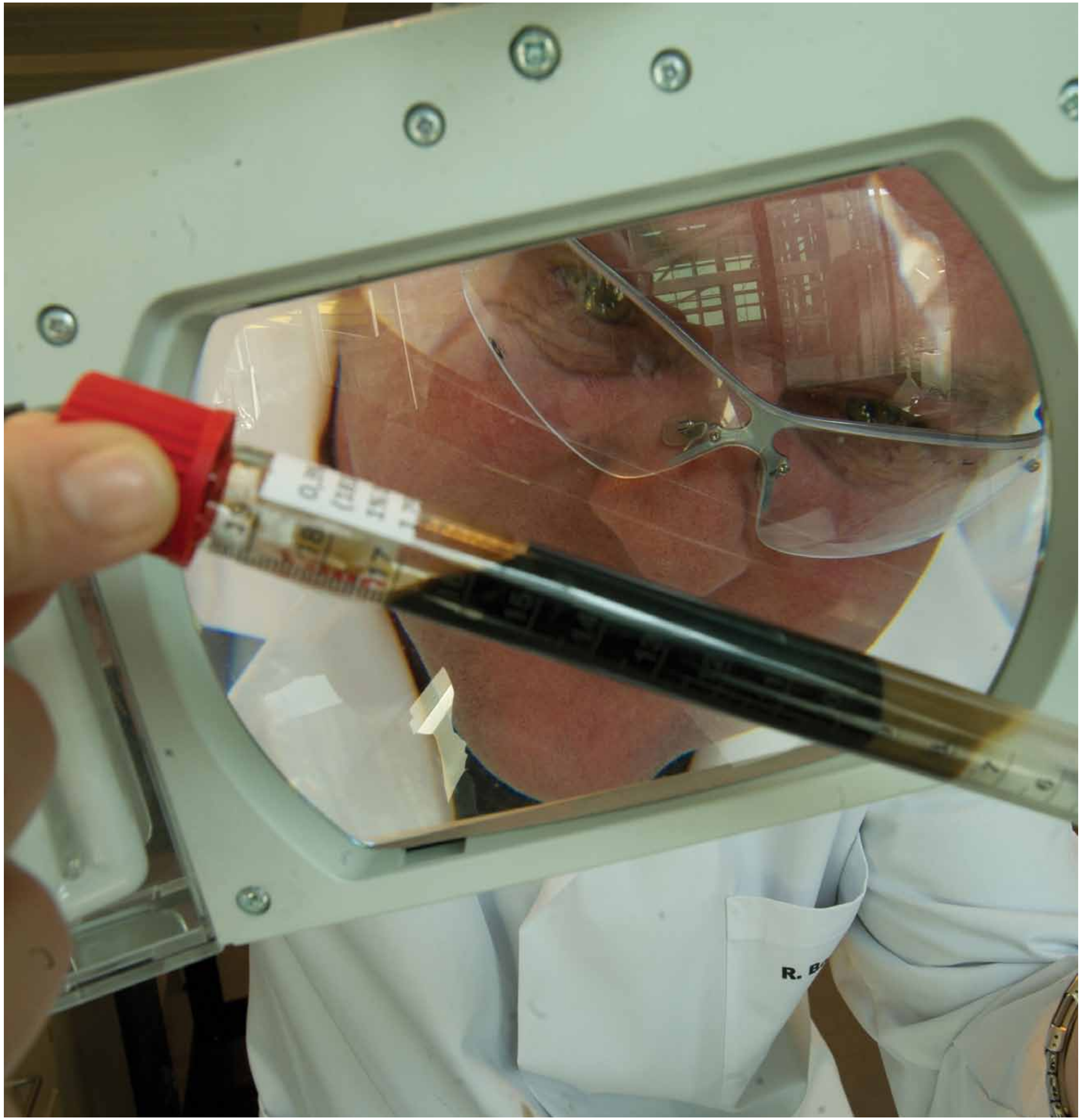
Marmul, Rima & RTQ
Polymer/ASP

Estimates suggest EOR accounts for 4% of global oil production: about 3 million barrels per day. The International Energy Agency believes that EOR could ultimately release 300 billion barrels of oil from fields around the world. This is a lot of oil – about 10 years of production at today's level. And yet the full potential is arguably greater than this; we cannot overlook the fact that two-thirds of the oil in place in the world's oilfields is currently unrecovered. The economic drivers to produce more oil are certainly strong: higher oil prices and forecasts of increasing oil demand. For its part, Shell is deeply committed to the EOR technology cause. Indeed, we have been committed for the past 40 years, during which time EOR has been a feature of the industry agenda. In this period, we have been responsible for breakthroughs in a range of technologies crucial to raising recovery levels and meeting higher production goals in oilfields of various kinds. Just as important, is what we have learned in the process: in laboratories, in pilot plants, in producing fields around the world and in collaboration with other oil companies, partners and leading service providers. Of all the techniques available, chemical EOR is perhaps the least well developed and probably offers most potential: in its own right and in combination with established waterflooding technology. Reservoir surveillance technology will be important to enable us to manage the chemical flooding process effectively: essentially to manage the chemistry in the reservoir. Effort is also needed to develop more effective chemical molecules and to find ways of making them more cheaply. Shell has a huge advantage in this regard, being able to call on the chemical knowledge and expertise in areas such as molecular modelling and advanced experimentation that exist in our downstream chemicals business.

Continuous technology integration is important. Shell combines pure chemical EOR technology with drilling and completions engineering know-how and skills in reservoir characterisation and management, and operational field management.

Finally, at Shell, we believe there has to be a philosophical change. It is not sufficient to think of EOR as an add-on, something that is considered later in the life of the field to revive flagging production. There has to be a life-cycle approach to EOR. The concept of energising the reservoir deserves attention from the earliest stages of field planning and development.

Shell has an outstanding record of leading the oil industry in terms of ability to explore for oil and produce it in ever more demanding environments. Significantly, our endeavours to extend the geographical frontiers are soundly matched by our efforts to pursue the more difficult oil in our existing assets, which require all our skills and experience to unlock.



Oil samples, Shell Technology Centre Rijswijk, the Netherlands

DISCLAIMER

Reserves: Our use of the term "reserves" in this brochure means SEC proved oil and gas reserves for all 2009 and 2010 data, and includes both SEC proved oil and gas reserves and SEC proven mining reserves for 2008 data. Resources: Our use of the term "resources" in this brochure includes quantities of oil and gas not yet classified as SEC proved oil and gas reserves or SEC proven mining reserves. Resources are consistent with the Society of Petroleum Engineers 2P and 2C definitions.

Organic: Our use of the term Organic includes SEC proved oil and gas reserves and SEC proven mining reserves (for 2008) excluding changes resulting from acquisitions, divestments and year-average pricing impact. To facilitate a better understanding of underlying business performance, the financial results are also presented on an estimated current cost of supplies (CCS) basis as applied for the Oil Products and Chemicals segment earnings. Earnings on an estimated current cost of supplies basis provides useful information concerning the effect of changes in the cost of supplies on Royal Dutch Shell's results of operations and is a measure to manage the performance of the Oil Products and Chemicals segments but is not a measure of financial performance under IFRS.

The companies in which Royal Dutch Shell plc directly and indirectly owns investments are separate entities. In this brochure "Shell", "Shell group" and "Royal Dutch Shell" are sometimes used for convenience where references are made to Royal Dutch Shell plc and its subsidiaries in general. Likewise, the words "we", "us" and "our" are also used to refer to subsidiaries in general or to those who work for them. These expressions are also used where no useful purpose is served by identifying the particular company or companies. ''Subsidiaries'', "Shell subsidiaries" and "Shell companies" as used in this brochure refer to companies in which Royal Dutch Shell either directly or indirectly has control, by having either a majority of the voting rights or the right to exercise a controlling influence. The companies in which Shell has significant influence but not control are referred to as "associated companies" or "associates" and companies in which Shell has joint control are referred to as "jointly controlled entities". In this brochure, associates and jointly controlled entities are also referred to as "equity-accounted investments". The term "Shell interest" is used for convenience to indicate the direct and/or indirect (for example, through our 24% shareholding in Woodside Petroleum Ltd.) ownership interest held by Shell in a venture, partnership or company, after exclusion of all third-party interest.

This brochure contains forward-looking statements concerning the financial condition, results of operations and businesses of Royal Dutch Shell. All statements other than statements of historical fact are, or may be deemed to be, forward-looking statements. Forward-looking statements are statements of future expectations that are based on management's current expectations and assumptions and involve known and unknown risks and uncertainties that could cause actual results, performance or events to differ materially from those expressed or implied in these statements. Forward-looking statements include, among other things, statements concerning the potential exposure of Royal Dutch Shell to market risks and statements expressing management's expectations, beliefs, estimates, forecasts, projections and assumptions. These forward-looking statements are identified by their use of terms and phrases such as ''anticipate'', ''believe'', ''could'', ''estimate'', ''expect'', ''intend'', ''may'', ''plan'', ''objectives'', ''outlook'', ''probably'', ''project'', ''will'', ''seek'', ''target'', ''risks'', ''goals'', ''should'' and similar terms and phrases.
There are a number of factors that could affect the future operations of Royal Dutch Shell and could cause those results to differ materially from those expressed in the forward-looking statements included in this brochure, including (without limitation): (a) price fluctuations in crude oil and natural gas; (b) changes in demand for the Shell's products; (c) currency fluctuations; (d) drilling and production results; (e) reserve estimates; (f) loss of market share and industry competition; (g) environmental and physical risks; (h) risks associated with the identification of suitable potential acquisition properties and targets, and successful negotiation and completion of such transactions; (i) the risk of doing business in developing countries and countries subject to international sanctions; (j) legislative, fiscal and regulatory developments including potential litigation and regulatory measures as a result of climate changes; (k) economic and financial market conditions in various countries and regions; (l) political risks, including the risks of expropriation and renegotiation of the terms of contracts with governmental entities, delays or advancements in the approval of projects and delays in the reimbursement for shared costs; and (m) changes in trading conditions. All forward-looking statements contained in this brochure are expressly qualified in their entirety by the cautionary statements contained or referred to in this section. Readers should not place undue reliance on forward-looking statements. Additional factors that may affect future results are contained in Royal Dutch Shell's 20-F for the year ended 31 December, 2011 (available at www.shell.com/investor and www.sec.gov). These factors also should be considered by the reader. Each forward-looking statement speaks only as of the date of this brochure, 29 February 2012. Neither Royal Dutch Shell nor any of its subsidiaries undertake any obligation to publicly update or revise any forward-looking statement as a result of new information, future events or other information. In light of these risks, results could differ materially from those stated, implied or inferred from the forward-looking statements contained in this brochure. There can be no assurance that dividend payments will match or exceed those set out in this brochure in the future, or that they will be made at all.

The United States Securities and Exchange Commission (SEC) permits oil and gas companies, in their filings with the SEC, to disclose only proved reserves that a company has demonstrated by actual production or conclusive formation tests to be economically and legally producible under existing economic and operating conditions. We use certain terms in this brochure, such as resources and oil in place, that SEC's guidelines strictly prohibit us from including in filings with the SEC. U.S. Investors are urged to consider closely the disclosure in our Form 20-F, File No 1-32575, available on the SEC website www.sec.gov. You can also obtain these forms from the SEC by calling 1-800-SEC-033

Any supply of the technology is subject to agreement on a contract and compliance with all applicable export control regulations.

ECCN: Not subject to EAR – Publicly Available

For further information on Shell technologies, contact: technology-news@shell.com

Design and layout by Graphics, Media and Publishing Services Rijswijk/P06509