THE SIGNIFICANCE OF ENHANCED OIL RECOVERY
LABORATORY WORK AND KNOWLEDGE TRANSFER
PILOTING AND FIELD TESTS
FULL FIELD, COMMERCIAL DEPLOYMENT AND OPERATIONS
EMERGING TECHNOLOGIES
The significance of enhanced oil recovery

Affordable technology plays a pivotal role in meeting current and future field developments.
World energy supplies will go through a major transition this century. Shell expects the global energy mix to evolve significantly with gas, the cleanest burning fossil fuel, becoming more widely used for power generation. Renewable energy sources such as wind, solar and biofuels are likely to become increasingly important, but oil and gas will continue to play a vital role in meeting the anticipated rise in energy demand.

To meet rising demand the oil and gas industry will have to maximise economic ultimate recovery from existing oil and gas fields. Global average field recovery from water flooding is currently around 35%, leaving between 60 to 70% of oil in place, and this represents a substantial opportunity.

Affordable technology will play a pivotal role to meet demand in the current business environment. Many current and future field developments will involve complex improved oil recovery (IOR) and enhanced oil recovery (EOR) projects, challenging fluids (heavy oil, sour gas), challenging reservoirs (tight formations, deep reservoirs, high temperature and pressure), or challenging environmental settings including deepwater locations.

With the increased complexity of new and mature fields each next step to improve recovery comes with increased cost. Operational excellence in primary and waterflood stages of field development is a prerequisite for successful
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IDEAS INTO ACTION

Innovative technologies are helping Shell improve recovery rates across our hydrocarbon portfolio. Our research includes projects on primary depletion, water-injection based recovery technologies (water flooding, low-salinity flooding, polymer, surfactant and water soluble solvents), gas-based technologies (water alternating gas injection, gas oil gravity drainage, miscible gas injection, high-pressure contaminated (CO₂/H₂S) gas injection, foam) and thermal applications (steam, steam foam, solvent steam, and steam assisted gravity drainage in fractured reservoirs). We are also looking at chemical polymers for high-salinity, high-temperature environments so that we can enhance recovery from even the most challenging oil fields.

CONSIDERING EOR AT AN EARLY STAGE OF FIELD DEVELOPMENT

For new field developments planning for enhanced recovery should be considered during field development planning. Effective field development studies enable operators to decide whether a particular project will be economic, help them screen project options and select the optimal full field development concept, including potential EOR techniques. The plan goes beyond technical capability and also examines commercial factors. Making a strong and realistic business case for the application of phased EOR projects is a crucial part of the development process.
Choosing the best recovery technique requires deep understanding of reservoir behaviour and oilfield economics.

Making a strong and realistic business case for the application of phased EOR projects is a crucial part of the development process.

Shell has been deeply committed to IOR and EOR technology deployment for more than 40 years, throughout the time these technologies have featured on the industry agenda. We have a strong track record of applying IOR and EOR with successful projects in waterflooding, miscible gas injection, thermal and chemical EOR.

Waterflooding has the advantage of lower capital and operational costs compared to EOR techniques. Around 30-40% of Shell’s oilfields are under waterflood. A lot of our tertiary recovery techniques are around how we can enhance recovery from existing waterflood systems. Hence considerable effort has been devoted to developing better water flooding processes, including low-salinity waterflooding (LSF). Although IOR/EOR costs are higher, the unit cost per volume of oil produced can be lower.

Shell is pursuing concerted recovery technology programmes in research centres in the Netherlands, Canada, the US and Oman. Our technology programme includes fundamental research in areas such as nanotechnology and the use of solvents; joint ventures on pilot trials and demonstration projects in Russia, Malaysia and the Middle East; and continuous improvement of technologies for full-scale projects in mature assets across the world.
DEMONSTRATE AND DE-RISK

Technology teams at Shell are focused on having their solutions tested, demonstrated and deployed. The technology development process covers everything from laboratory tests to full-field commercial application. De-risking is a crucial part of the process. Applying EOR techniques in an oilfield involves careful interpretation of the reservoir volume and design of each programme, including the use of detailed simulation models and thorough field trialling.

Technology matures from phase behaviour studies and core floods in the laboratory to single well tests in the field and, ultimately, to commercial field deployment. Our scientists and experts provide experimental work, analysis and support for the deployment process, working with field and reservoir engineers to understand their needs and the project value drivers.

End-to-end solutions to optimise field performance and maximise economic recovery

Interpret/design with models that include appropriate physics and chemistry

Phase behaviour
- 2 months
  - Optimal salinity
  - Solubilisation

Core floods
- 3-12 months
  - Incremental oil production
  - Chemical consumption
  - Calibrate models

Single well test
- 1-2 months
  - Injectivity
  - Remaining oil saturation
  - Chemical efficiency

Multiple well field test
- 2-5 years
  - Sweep efficiency
  - Chemical consumption
  - Reservoir heterogeneity
  - Operational experience
  - Create saleable oil
  - Fluids handling scaling
  - Surveillance options
  - Validate predictive capability

Commercial operation
- 3-10 years

The development of a new EOR technology will require several years from initial laboratory work to full field deployment.
Shell has EOR projects at different stages of deployment around the world and across the whole spectrum of waterflooding operations, from rejuvenation of brown fields to green field developments (offshore and onshore)
Laboratory work and knowledge transfer

Shell laboratories provide the crucial crossover between research and top-end technical services.

Core samples, Shell Technology Centre Rijswijk, the Netherlands

Shell Technology Centre Westhollow, Houston, USA
Laboratory testing plays a central role in efforts to boost recovery and Shell laboratories provide the crucial crossover between research and top-end technical services. This provides a link between fundamental understanding of scientific principles and the necessary insights to apply affordable technology in the oil field.

**THE IMPORTANCE OF LABORATORY CAPABILITIES**

Our Shell laboratory staff work closely with asset study teams, providing experimental input and analysis and conducting technology trials in the field. Our scientists want and expect to make a strong contribution to the success of operations and this includes playing a key role in the deployment process for methods such as chemical EOR, which may involve working as part of an integrated technical team with several partner companies.
SCREENING FOR SUCCESS

Shell laboratories conduct two distinct screening processes for EOR applications. The first involves screening fields to determine which technologies are most suitable for conditions in that field. The second involves screening the chemical systems (surfactants, polymers or controlled water quality) to suit the specific field. This twin-track approach is essential for the success of EOR programmes: the chemical combinations we select must be suitable for the temperature, oil chemistry and formation water chemistry that will be encountered in the reservoir.

Screening and optimising in the laboratory helps to increase the probability of planned treatments boosting recovery factors. The laboratory teams work closely with the teams in the field because there may always be differences between what can be achieved in the laboratory and what is observed in the reservoir, where issues such as sweep efficiency and geological complexity will reduce performance.

Effective screening requires a range of analytical techniques and some of the most important recent developments are described in the sections below.

TURNING CORE ANALYSIS AROUND

X-ray computed tomography (CT) scanning has become an essential technology to study fluid flow through rock samples.

CT scans reveal the rock structure and the movement of fluids ranging from what happens at the individual pore level with micro-meter resolution to experiments with several meter long samples.

As not one single CT scanner covers this large spread of length scales, Shell has mobilised a wide range of scanning technologies.

This does include executing experiments at international synchrotron facilities. These allow studying very fast fluid movements at the scale of individual rock pores.

In addition Shell has established in-house experimental capabilities based on both commercial available and for Shell custom built instruments.

With these instruments Shell investigates fluid movement in real rock samples under reservoir temperature and pressure conditions from millimetre to several meter length.

IMPROVING YOUR IMAGE - DIGITAL CORE ANALYSIS

Core flooding studies help scientists understand pore-scale displacement processes in the reservoir rock and are essential for de-risking of EOR projects. However, core flood tests can be expensive and time-consuming and are typically destructive – the core is altered during testing – so tests cannot be repeated on identical samples.

Shell is developing digital techniques that can assess pore-scale displacement and support early-stage derisking. Digital core analysis (DCA) uses high-resolution, micrometre-scale 3D images of rock samples and simulates processes such as fluid flow, electrical transport and elastic deformation in porous media. It can also be used to study pore fluid displacement processes using in-situ imaging with specially designed flow/stress cells.

It may be possible to use DCA to determine rock elastic and mechanical properties. This could be used for scenario testing in quantitative interpretation petrophysics, for example, by varying fluid or grain properties, or as a research tool for understanding reservoir depletion.
UNRAVELLING THE COMPLEXITY OF CRUDE OIL COMPOSITION

Hydrocarbons are complex mixtures of chemicals and the molecular composition of these fluids directly controls their properties and stability. Until recently, the main molecular tool that petroleum geochemists applied to exploration and production issues was gas chromatography – mass spectrometry (GC-MS). This was very successful in conventional oil fields, but less so in reservoirs with heavy oil and oil sands bitumen.

Shell geochemists have introduced techniques that offer a more complete understanding of crude oil composition. One of these, known as Fourier transform ion cyclotron resonance mass spectrometry (FTICR MS) offers ultra-high resolving capabilities and has been successfully applied to the study of heavy and unconventional crude such as bitumen and shale oil.

The wealth of data from FTICR MS enables scientists to assess the high polarity constituents that can cause problems during production and transportation/pipelining and refining of heavy oils. Being able to identify problem-causing components in petroleum will help to solve many problems such as flow assurance, corrosion, the origin of stable emulsions and well plugging.
RAPID 3D IMAGING OF FLUID SATURATIONS IN ROCK CORES

Core flooding experiments help us understand oil recovery mechanisms. To interpret core-flooding data correctly, scientists need effective imaging of fluid distributions within the core sample. These images are often obtained using techniques such as magnetic resonance imaging (MRI).

MRI can help differentiate between chemical species and establish the fluid content of pores. Unfortunately, the conventional acquisition strategies for MRI data are too slow to capture the dynamic displacement processes that take place during core flooding. Shell has overcome this challenge by adapting the standard MRI method.

The new Compressed Sensing (CS) MRI method enables scientists to reconstruct very high-quality images of the sample from significantly fewer measurements than was previously thought necessary. This means that CS-MRI can acquire 3D images of the fluid saturation in a rock core in minutes rather than hours, enabling Shell to capture 3D fluid saturation images during laboratory core-flood tests and examine important dynamic processes.

MEASURING FLUID CHANGES IN THE OIL FIELD

Reservoir changes during recovery programmes can be measured using time-lapse saturation logging at observation wells between the injectors and the producers. In some reservoirs, however, the EOR process makes it difficult to interpret conventional saturation logs. For example, injected fluids that change the aqueous phase salinity by an unknown amount make the interpretation of resistivity and sigma logs uncertain, while fluids that change wettability will introduce errors in the interpretation of resistivity logs.

Nuclear magnetic resonance (NMR) is a fluid-volume-sensitive measurement that can clarify what is happening within EOR reservoirs. However, conventional observation wells are completed in cemented steel casing and NMR can only be applied if the well casing is nonconductive and nonmagnetic.

To help a Middle East operator assess the effectiveness of EOR programs (including polymer, surfactant and alkaline surfactant polymer methods) Shell combined NMR logging and fibre-reinforced plastic (FRP) casing in observation wells. This delivered key surveillance information, including flood front advancement monitoring, fluid type identification/quantification, and most importantly, residual oil saturation changes with a precision to within 5-saturation units.
KNOWLEDGE TRANSFER FOR RESEARCH AND INNOVATION

Laboratory support is crucial to the success of EOR deployments. Shell is working with KazMunayGas (KMG), Kazakhstan’s national oil company, to support an ambitious innovation agenda that is being promoted by the country’s national government. As a committed foreign investor, Shell is helping to align the agenda with the business needs of industry. As part of our commitment to the roadmap, we have been helping to establish facilities and develop the skills of professional staff for a new geochemistry laboratory in Atyrau, Kazakhstan.

The laboratory will provide geochemical services and research for exploration, development and production using a range of new technologies, including geochemical ‘fingerprinting’. The introduction of these technologies and associated expertise may provide high-quality data for operators across Kazakhstan, enabling them to improve field economics, extend field life and maximise oil production with the fewest number of wells and at minimum cost.

Robotic viscosity measurement for chemical EOR, the Netherlands
Piloting and field tests

Pilot studies and field tests – a first step towards full commercial deployment
Once the initial laboratory studies and screening have been completed, a next step towards executing a successful EOR project is to execute well tests in the field.

During single well tests, the development team can confirm reservoir injectivity and assess remaining oil saturation before and after chemical injection to confirm the effectiveness of the injected formulation. If the single well test is successful, the field operator may choose to conduct a multiple-well pilot to determine sweep efficiency, chemical consumption and effects of reservoir heterogeneity. The multiple-well pilot also enables operators to gain experience of EOR in the specific field, create saleable oil, define fluid handling procedures to prevent scaling and evaluate cost-effective reservoir surveillance options.

The examples in this section describe some of the locations where new Shell technologies are being piloted in the field.
CHEMICAL SCREENING AND MANUFACTURE

Surfactants have been used for oilfield applications since the 1970s. The molecular structures of surfactants used for EOR are matched to specific reservoir conditions through laboratory tests that screen for aqueous solubility and crude oil/water interfacial tension.

Surfactant molecules must match the crude oil composition to produce the ultra-low interfacial tension that mobilises trapped oil. It must also prevent the formation of high-viscosity emulsions and be soluble in the injection fluid and stable at reservoir temperature.

The physical form and properties of manufactured surfactants are also important for shipment, handling and mixing at EOR surface facilities. Full-scale projects require very large volumes of surfactant with consistent composition and performance because surfactants are manufactured and supplied in batches over the months or years of a field project. Shell is in a leading position among IOCs with respect to surfactant screening, modelling, manufacture and delivery.

As chemical EOR projects move to the full field commercial scale, with large surfactant volume requirements, surfactant manufacturers and oil companies will have to align operational needs and surfactant manufacturing capacity. Future research and development work will focus on simplifying supply logistics and reducing the costs associated with handling and mixing at surface facilities.

ALKALINE SURFACTANT POLYMER IN OMAN

Alkaline surfactant polymer (ASP) flooding involves injecting an aqueous solution comprising a slug of alkali, surfactant and polymer to release trapped oil and move it towards producing wells. This technology has passed through all the stages from laboratory work to early field application. ASP has the potential to recover a significant fraction of the oil that remains in the reservoir after conventional waterfloods.

Petroleum Development Oman (PDO, JV partner, 34% Shell), supported by Shell Projects & Technology in Oman and Rijswijk, has identified significant target-oil volumes for ASP flooding and carried out a sequence of single-well pilots in three fields, sandstone and carbonate, to assess the effectiveness of tailor-made chemical formulations under real sub-surface conditions and to quantify the benefits of full-field ASP development.
In Russia, Shell P&T have been working with our joint venture company Salym Petroleum Development (SPD), to conduct a series of laboratory and field tests in the Salym field. These have been completed with impressive results. The use of the ASP technology in a single well tracer test demonstrated the displacement of 90% of the oil left in the formation after conventional waterflooding.

SPD are about to execute a pattern-flood pilot similar to the one in Oman. The wells have been drilled and cemented, the construction of the facilities is to be completed in Q1 2016, while ASP injection is expected to start in Q2 2016. The result of the pattern pilot will provide information on the chemical retention of the injected formulation, on its ability to mobilize the oil remaining after water flooding and if and how produced chemicals affect the oil water separation in the production facilities. If the results are positive, the chemical cocktail can be fine-tuned and the full field reservoir simulation will be updated. This will aid the optimisation and commercialisation of ASP on a larger scale.

The extensive design process included optimisation of chemical phase behaviours in test-tube and core-flood experiments. The key chemicals and flow properties of an ASP flood were captured to calibrate comprehensive reservoir-simulation models. The models were used to evaluate PDO’s single-well pilots. The results have been used to design a pattern-flood pilot, which started injecting ASP in Q1 2016.

**ALKALINE SURFACTANT POLYMER AT SPD SALYM, RUSSIA**

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APPLYING ASP IN OFFSHORE ENVIRONMENTS

In ASP flooding sodium carbonate is generally used as the alkali. However, Shell is considering the use of anhydrous liquid ammonia dissolved in aqueous brine, which produces an ammonium hydroxide solution with buffered alkalinity that is similar to sodium carbonate solutions.

The low molecular weight of ammonia means that six times less alkali is needed to produce the alkalinity required by an ASP formulation. This could lower project costs and simplify logistics in situations where space constraints are critical, for example, in offshore operations. Shell has investigated how the use of ammonia would affect the key factors that influence recovery. Core flood tests have resulted in high recovery of crude oil with an ammonium hydroxide alkali surfactant polymer (AASP) formulation, which demonstrates the potential for this form of alkalinity.

Together with our joint venture partner Petronas we are piloting an EOR project for the St. Joseph field offshore North Sabah — which if successful could be the world’s first ASP application offshore. Project economics are clearly challenged in the current environment and we are looking at replacing conventional alkaline solutions with ammonia, for example, or even straight seawater based formulations without alkali which reduces transportation costs which are a major cost element in many offshore EOR developments.

HYBRID SYSTEMS TO REDUCE UNIT COST

Today we are looking at different hybrid systems, combining water flooding with polymer or surfactants in different ways, to make the facility side easier to implement and more affordable, in the drive for improved recovery in the current economic environment. The objective is to reduce the unit cost so that such developments are competitive or lower when compared to conventional waterflooding.

SURVEILLANCE TECHNIQUES – TRACKING RESERVOIR CHANGES OVER TIME

At Shell, we are aiming to increase recovery across our global portfolio by an average of 5%. To meet this target we will have to extract more oil from a variety of reservoirs while reducing unit costs and energy use.

In addition to reservoirs that are more challenging and more complex field developments, the business environment is driving changes that include working in more environmentally sensitive areas, and increasing governmental regulation. Given this increasing complexity, it is critical that we gain a better understanding of the subsurface. A clearer understanding will enable us to make better decisions, optimise technical integrity, preserve our license to operate and optimise field performance and maximise economic recovery.

To ensure that recovery technologies deliver to their full potential, we focus on well, reservoir and facility management. This integrated approach requires modern information technology and data acquisition and management capabilities.

Our current focus is on developing and implementing improved 4D seismic methods, next generation sensors and systems for areal and in-well monitoring, in particular integrated fibre-optic solutions for real-time well, reservoir and...
pipeline surveillance for use both onshore and offshore. We have forged partnerships with leading technology providers such as Baker Hughes, QinetiQ/OptaSense, Sonardyne, CGG, Smart Fibres and FairfieldNodal and have long-term relationships with universities and research institutes such as TNO and Delft University.

Shell has applied surveillance methods on many fields within its portfolio, delivering increased recovery, accelerated production, reduced cost and improved HSE performance. The value potential in future fields is considerable, but more challenging as these fields are often located in difficult or new areas. Therefore, our current focus is on developing and implementing improved 4D seismic methods (OBS, i4D, PRM, fibre optic etc.) to address these challenges.

**SHELL PETROSIGNS***

The foundation of effective field development, for new and existing reservoirs, is the quality of joint decision making by the asset team. Working together more effectively and sharing information more easily is essential to ensure that asset teams select the best development plans and optimise recovery.

Our PETROSIGNS platform combines geological and reservoir modelling capabilities to help teams optimise both field development and hydrocarbon recovery. In order to take the best field development decisions we need to understand the uncertainties and represent these in the modelling process. The platform supports the integrated workflows that are key for transferring knowledge and quantified uncertainty between technical disciplines. It provides a common working environment for Production Geology, Petrophysics, Reservoir Engineering and Production Technology staff.

The PETROSIGNS platform will also enable adopting a single data repository for Shell teams accelerating the introduction of proprietary technologies and reducing life cycle costs.

PETROSIGNS Dynamic Modelling has been deployed at Perdido with more deployments planned in 2016.

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Full field, commercial deployment and operations

To maximise recovery there has to be a life-cycle approach to EOR
Once a technology has proved its value in the laboratory and achieved success in various pilot programmes, it may be chosen for a full field development project. Moving to full field deployment is a major decision and the process will require substantial investments of time and resources.

The examples below illustrate some of the challenges we have overcome in commercial-scale deployment projects and highlight some of the additional benefits, such as improved operational performance or increased facility uptime, which EOR technologies can deliver.

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Working independently or in collaboration with industry partners and the academic sector, Shell has taken many technologies from concept to field application. Once the decision to proceed to full field deployment has been taken, the main challenges are managing the technical requirements of upscaling EOR technologies from pilot to field-wide applications, maintaining a focus on the quality of the operations and managing costs.
**POLYMER**

Polymer systems are established technologies that have been used to improve waterflood efficiency for several decades. Experience has shown that polymer floods can deliver a 5-15% increase in recovery factor and help to increase the commercial contribution that an asset makes by enabling the field operator to produce oil more quickly. The rapid increase in production can help to achieve rapid project payback. Polymer floods are suitable for most waterflood operations and require only moderate changes to operating facilities. They have proved particularly effective in reservoirs that contain medium-heavy oil. Front planning of a polymer flood can improve the economics of capital intensive projects. Schiehallion’s new FPSO has been designed to accommodate polymer injection. Once technically de-risked, a polymer flood will improve the water injection scheme and increase the oil recovery in an economically attractive way.

Recent studies have shown that in heterogeneous reservoirs with light oil, polymer can yield incremental recovery also from 5 to 15%. Together with fine tuning the polymer slug size, injection volumes can be optimised and complication from polymer in the produced fluids minimised. We call this lean polymer flooding.

**LOW SALINITY WATERFLOOding**

Estimates suggest that low salinity waterflooding (LSF) can improve oil recovery by up to 6% oil initially in place. LSF is a natural extension of conventional waterflooding, but the process of screening, designing and executing LSF projects requires an increased operator competence and long-term management focus. However, operators that invest in the water treatment facilities required for LSF will have cleaner water in their production system, which typically results in better operational uptime and increased facility reliability.

To accelerate the deployment effort for LSF, and standardise the facilities design, integrated technology teams collaborate closely with our R&D and asset teams. This has led to a number of technical advances. For example, Shell has recently identified the fundamental controlling mechanism for low salinity waterflooding in carbonates. This significant breakthrough was based on a combination of fundamental expertise in carbonate reservoirs, a dedicated in-house EOR research group that specifically targets carbonates and collaboration with leading university teams.

**MARMUL**

Maximising recovery from existing oil fields is vital, especially here in the Middle East. But currently, in fields that use traditional water flooding, 60 to 70 per cent of the oil is left in place. Changing that statistic presents a huge opportunity. PDO is making the most of it in Oman, by switching from water to polymer flooding in the Marmul field. The polymer flood project started up in 2010 and already has produced more than 1 million m³ of incremental oil. PDO is now expanding this success story, to create one of the largest polymer flooding facilities in the world.
TAKING LOW SALINITY FLOODING OFFSHORE

Lowering the salinity of injected water boosts the efficiency of waterflooding. The less salt there is in the water, the easier it is to dislodge oil from pores in the reservoir rock. Low-salinity waterflooding (LSF) requires large volumes of low-salinity water and Shell has developed technologies that can be used to transform seawater into low-salinity injectant.

Water treatment for LSF involves a two-step process of nanofiltration and 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, which removes the salt from the water. By modifying seawater to match its properties with the characteristics of the rock, the oil and the water in the reservoir, we can make it easier to move oil away from the pore walls in the reservoir rock and so increase oil recovery rates.

HYBRIDS AND OFFSHORE

LSF is likely to prove extremely valuable for offshore projects. Replacing seawater with low salinity water in polymer flooding, for example, could cut polymer consumption by between 5 and 10 times. This would deliver significant cost savings and lower storage space requirements on offshore installations in addition to the potential recovery benefits of LSF itself. Shell and its partners are applying this technology to raise production levels from fields in the North Sea, the Gulf of Mexico and other offshore areas.

MISCIBLE GAS FLOODING

Miscible gas flooding is a very effective way of maintaining reservoir pressure and raising oil production rates. The gases most 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.

PDO TAKES THE LEAD IN MISCIBLE SOUR GAS FLOODING

Our experience in miscible sour-gas flooding is being put to good use by PDO under a technical collaboration on sour hydrocarbons. Oman’s Harweel field cluster, for example, contains more than 60 wells drilled into reservoir structures characterised by 100-meter-thick carbonate stringers. These slabs of carbonate rock lying at depths of 2.5–5.0 km are encased by salt and contain light sour oil. During the first phase of the project, when production levels were about 18,000 bbl/d, miscible gas containing 3–4% hydrogen sulphide and 10–15% carbon dioxide was injected into the Zalzala field and confirmed the viability of miscible sour gas injection. The objective now is to extend the scheme to similar fields.
ENHANCED OIL RECOVERY USING HEAT

We are working with joint venture partner Petroleum Development of Oman (PDO) on a variety of thermal EOR initiatives. The projects at Amal and Qarn Alam in Oman are key examples of complex and well-managed steam floods. Moreover, Qarn Alam is the world’s first steam flood in a fractured reservoir and Amal is currently one of the deepest reservoirs being developed using steam drive methods.

RE-ENERGISING AN IMPORTANT HYDROCARBON ASSET

The Schoonebeek oil field in North-Western Europe was discovered in 1943 and production began in 1947. However, in 1996, the operators NAM terminated oil production at the field because the heavy viscous oil had become increasingly difficult to recover with the techniques and infrastructure available. Redevelopment of the Schoonebeek oil field, work began in January 2009. In January 2011 NAM recommenced oil extraction from the Schoonebeek oil field using new techniques such as horizontal wells combined with low-pressure steam injection and high-efficiency pumps. This is the largest onshore oil extraction project in Western Europe. The goal for this redevelopment plan is to increase recovery in the target area. Peak production is expected to be 20,000 barrels a day.
WEIGHING UP THE OPTIONS – NEW TECHNOLOGIES FOR EXTRA HEAVY OIL

In thermal EOR projects, it is vital to monitor changes in the reservoir that have been induced by the treatment. Seismic monitoring can provide information on large subsurface volumes and reveal the influence of treatments between wells.

However, although well established in offshore reservoirs, seismic monitoring is not widely used for onshore assets. This is due to mature onshore developments having a relatively high-density of wells and technical challenges such as the variability of the near-surface zone, changes in source and receiver coupling to the formation, complex and evolving infrastructure, high noise levels and the relatively high-cost of seismic operations in forested or populated areas.

Shell is working to overcome these issues and has applied a range of innovative geophysical technologies for monitoring thermal EOR operations in diverse onshore locations including The Netherlands, Canada, and Oman.

REDUCING UNCERTAINTIES IN RESERVOIR AND WELL PERFORMANCE

Working in collaboration with CGG, Shell has installed a 4D seismic monitoring system (SeisMovie™) a permanent reservoir monitoring (PRM) installation at Schoonebeek, the Netherlands. The SeisMovie system comprises permanently buried seismic sources and receivers, refraction seismic, down-hole seismic, and a newly developed Distributed Acoustic Sensing (DAS) method that enables low-cost and non-intrusive seismic surveillance.

A similar PRM system was installed at Peace River, Canada. This is the world’s largest onshore permanent reservoir monitoring (PRM) installation that is delivering real-time surveillance of a thermal EOR project.

Continuously acquired seismic data is being integrated with other surveillance techniques to monitor reservoir activity. The information enables the field operator to monitor steam conformance, adjust injection and production schedules and optimize recovery. Seismic acquisition has been performed 24/7 since May 2014 and the resulting data is processed in real time, delivering daily 4D seismic reservoir attributes and providing insights into reservoir activity insights that would have been missed with conventional time-lapse 4D seismic.
Emerging technologies

Science in a business context
Realising the full value of an asset requires creativity, vision and a pro-active approach. In R&D efforts Shell considers end-to-end solutions, so the technologies that emerge must be designed and delivered with a full understanding of how they fit into the specific system where they will be deployed.

Over the past 10 years, Shell has made substantial changes in its approach to innovation and technology development. We recognise that the global innovation footprint is large and diverse. The challenges that the energy industry faces and the solutions that are made possible by global technology development are varied. Many different organisations play a part and operating companies must be alert to new possibilities and work to benefit from the richness of knowledge that is available.

We operate a global ‘open innovation’ strategy for all our technology developments and collaborate with our business partners, universities and research institutes, suppliers and customers. Innovation is not just about new technologies and new processes. It is also about new ways of thinking to create value. There are two principal requirements for success: one, integrated and speedy technology delivery from development in the laboratory through to deployment in the field; and two, having a clear understanding of current and future business needs, and the technologies that respond best to them.
In the current oil price environment we are challenged. We drive innovation based on the premise of value; this includes value creation with clearly affordable technologies to enable increased competitiveness and direct contributions to Shell’s businesses and bottom-line. Right from the start of technology innovation projects there is a need to focus on how we can commercialize new technologies.

Working collaboratively is the key to success. External research and development institutes and technology innovators, such as academia, play an increasingly important part in our innovation efforts. How we deliver that whilst keeping focus on the value, requires continued close, sustained long-term relationships and deep collaboration, plus a systematic approach to ensure connectivity is maintained.

**COLLABORATION FOR TECHNOLOGY DEVELOPMENT**

Operators face a wide range of challenges in their attempts to maximise recovery from oil and gas fields. Typically, EOR techniques have to be adapted to meet the needs of each reservoir and the adaptation process helps to stimulate ideas for new methods and new applications.

Today, Shell and its partners are focused on finding new and more effective ways to apply EOR technologies and on extending the range of reservoir conditions in which they can be successfully deployed.

In this section, we outline some of the latest technological developments and examine the potential for emerging EOR techniques. Collaboration is a key part of EOR research and Shell laboratories maintain strong links to the academic sector. Our work with universities has grown significantly over the past ten years and we are continuing to expand this network.
BOOSTING RECOVERY FROM HOT, TIGHT AND SALINE RESERVOIRS – ENHANCED WATERFLOOD

Shell is examining the use of water-soluble solvents to enhance conventional waterfloods and has developed a method that can be applied in reservoirs that are too hot, tight or saline for more conventional EOR.

As the solvent is water-soluble, it can be very effectively back recovered from the reservoir. At the separation facilities hydrocarbons are extracted and sent for refining, while the water produced from the reservoir is divided into its key components for re-injection. The result is a significantly higher ultimate oil recovery compared to the conventional waterflood as well as accelerated oil production. The overall findings demonstrate that water-soluble solvent technology can increase oil recovery, from both carbonate and clastic cores, by 10-15% on top of the waterflood.

HARNESSING THE POWER OF THE SUN

Shell was involved in the Amal Solar EOR pilot project in Oman, a highly innovative thermal recovery programme that uses solar power for steam generation.

Thermal EOR is often criticized for its CO₂ intensity, but GlassPoint Solar technology uses solar mirrors – not gas – to generate steam for oil recovery.

Innovation often calls for collaboration between organisations of vastly different sizes and structures. In this case, the collaborators are GlassPoint Solar Inc., a technology company from California; Shell Technology Ventures (STV) Fund 2, that championed the use of GlassPoint technology; and Petroleum Development Oman, which has significantly invested in innovative EOR technologies and has successfully, piloted this technology.

The mirrors concentrate sunlight on a boiler tube containing water to produce high-pressure steam, which is injected into a reservoir to heat heavy oil and boost production. This leaves the gas resources in the ground or makes them available for industrial applications that can benefit economic growth in the Sultanate.

The GlassPoint project has continued to exceed contracted performance targets since operations began in 2012. The pilot generates an average of 50 tons of steam daily and serves as an operational baseline for potential large-scale projects in Oman and throughout the region.
NEW FRONTIERS IN FOAM FLOODING

Foam flooding has been intensively studied as a method to enhance oil recovery. Unfortunately, surfactant-generated foam has limited stability in the presence of oil. This and the poor chemical stability of surfactants in the high temperature and high salinity conditions of a typical oil reservoir have counted against the general application of foam flooding as an EOR tool.

However, recent studies conducted by Shell and the University of Delft, suggest that synthesized nanoparticles with altered surface properties can aid foam generation and increase foam stability in porous media. Both sandstone and carbonate rocks have been evaluated using readily available silica-based nanoparticles that can be processed economically without separate surface treatment.

A TINY TECHNOLOGY WITH HUGE POTENTIAL

We are conducting research aimed at applying nanotechnology to achieve maximum recovery of oil and gas from new and existing reservoirs in the near future.

We have a nanotechnology laboratory in the USA and we are a founding member of the Advanced Energy Consortium (AEC), which is a joint-industry consortium set up to facilitate pre-competitive research into micro- and nanotechnology materials and sensors. We also collaborate with MIT in the USA on projects involving nanotechnology for subsurface applications.

The implications of applying nanotechnology to enhance oil and gas recovery are very exciting. Nanotechnology may help us achieve things that once seemed impossible. The right design of nanoparticles can stabilise foams and emulsions in the reservoir to improve sweep efficiency and recover oil from otherwise bypassed zones.

COLLABORATION ON NANOPARTICLE SURFACTANTS

As part of the Advanced Energy Consortium, Shell is working with academics from 30 universities across the world and engineers and geoscientists from various oil and gas companies to explore the potential of applying nanotechnology to oil and gas projects.

For example, one strand of AEC research involves a team at Rice University in Houston, USA working to create nanoparticles that can provide a more robust alternative to surfactants. Surfactants have a polar head that mixes with water and a nonpolar tail that mixes with oil. By attaching hydrophilic and hydrophobic molecules to the surfaces of nanoparticles, the AEC team is aiming to modify the low-cost particles so that they can easily disperse in water and mobilize the oil.

Shell employee examining a microfabricated sensor, which integrates nanoscale sensing elements, developed at University of Michigan, during the Annual AEC’s All Projects Review Conference held at Shell Technology Center Houston.
CARBON, CAPTURE AND STORAGE WORKS

In November 2015 we celebrated the official opening of the Quest carbon CCS project in Alberta, Canada. Quest is designed to capture and safely store more than one million tonnes of CO₂ each year – equal to the emissions from about 250,000 cars.

A key concern heard throughout the consultative process was around safety and potential for local environmental impacts from the project. Educating the public about the CCS process and its safety record was an important step towards gaining local stakeholder acceptance.

The Quest project also bore cost to develop technology, legislative and regulatory frameworks which can now be used as templates for replication to reduce front-end-project costs for follow on projects. With the experience of operating the Quest carbon-capture facilities, areas are being identified in which contingencies in the design could be reduced.

MEASUREMENT, MONITORING AND VERIFICATION

The Quest project has a responsibility to carefully monitor activity within the storage area and to verify that the CO₂ remains permanently trapped in the subsurface. To this end, a comprehensive measurement, monitoring and verification (MMV) program is in place, which is considered to be one of the most innovative aspects and demonstration elements of Quest.

The current MMV program covers a wide range of technologies and analysis throughout the atmosphere, biosphere, hydrosphere and geosphere. For instance, it includes fibre optic cables as distributed acoustic sensors (DAS) for vertical seismic profiling (VSP) in wells and LightSource technology, which is capable of sniffing air and finding CO₂ leaks to the atmosphere very sensitively over an extended region away from the well.

The program has been designed to ensure conformance - to indicate the long-term effectiveness of CO₂ storage by demonstrating actual storage performance is consistent with expectations about injectivity, capacity, and CO₂ behaviour inside the storage complex.

And the program has been designed to ensure containment - to demonstrate the security of CO₂ storage and to protect human health, groundwater resources, hydrocarbon resources, and the environment.
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© Shell Global Solutions International B.V.
Kessler Park 1, 2288 GS Rijswijk, the Netherlands

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

Designed and produced by:
24812 – PCoE, The Hague