EOR
MAXIMIZING
RECOVERY
FACTORS
Improving the recovery factor of conventional oil resources will play a decisive role in offsetting the inevitable decline of oilfields.

By pursuing a dedicated research and development program, Total is positioning itself among the future industry leaders in the field of EOR.

To maximize the recovery of a wide range of target resources, injections of chemicals, CO₂, steam or water with controlled salinity are some of the diverse options available. From the most basic research to the most daring operational pilots, every field of expertise is being mobilized.

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Total worldwide in 2008
Total’s Exploration & Production branch continually pushes oil and gas production to new limits. Drawing on the complete integration of its multidisciplinary expertise, the Group has honed a capacity for innovation that has secured its rank among the frontrunners in the technologies strategic to the future of the energy industry.

Total’s Exploration & Production branch is involved in all of the industry’s key technological challenges, namely, extra-heavy crude oil, ultra-deepwater offshore, sour gas, hydrocarbon resources that are deeply buried (high-pressure/high-temperature) or difficult to produce because they are in “tight sand” reservoirs. At the same time, the Group is inventing the tools and techniques required to access residual reserves on conventional acreage.

Relying on synergies with other Group branches operating in the fields of gas and power, refining and marketing and petrochemicals, the E&P branch proposes technological solutions that cover the complete value chain from production to finished products and/or markets.

“Innovation will be the main driver of sustainable growth in our production.”
Improving the recovery factor of conventional oil resources will play a decisive role in offsetting the inevitable decline of oilfields and keeping step with the world’s demand for hydrocarbons.

To sustain global production of energy resources, it is imperative to recover more conventional reserves. Enhanced Oil Recovery (EOR) methods are among the key ways of achieving this goal. The stakes of this technology are certainly high: with the specter of peak oil looming as more and more existing oilfields reach maturity and accessible exploration targets become increasingly scarce, global production from conventional acreage is declining at a rate of about 5% per year. Meanwhile, in a scenario of medium-term global economic growth, demand will increase by about 1 to 1.5% per year. Of course, future discoveries through exploration efforts in frontier domains, coupled with profitable and large-scale production of unconventional resources made accessible by new technological developments, will help bridge the gap between these two diverging curves. However, most of the conventional oil reserves remaining today are confined to fields discovered at least a quarter of a century ago. It is easy to see why extracting a significant quantity of the residual oil bypassed by conventional recovery methods has key implications for the world’s energy future. Today, considering an average recovery factor of 32%, global proven oil reserves are estimated at around one thousand billion barrels (Gb) — as much oil as has already been produced to date. A 5% increase in that recovery factor would yield 300 Gb of additional reserves — as much oil as is expected from future exploration efforts.

However, regardless of the processes or products they employ, EOR technologies are costly. Boosting recovery factors by altering the flow efficiency at both the macroscopic and microscopic levels has an impact on the technical budget: in some cases, crude prices must be high for the additional recovery to be economically viable. Nevertheless, because these technologies will be an essential component of tomorrow’s production, Total is already making them a primary focus of its Research & Development (R&D) strategy.

Forecast gap between demand and production of oil.

Source: Total
The Group’s decision to establish a dedicated research program and carry out a number of development projects within the framework of a cross-disciplinary organization sends clear signals about Total’s ambition: to rank among the industry operators who will successfully meet the challenges of EOR. From laboratory research to field operations, Total is directing its efforts at offshore as well as onshore targets, with special emphasis on the complex carbonate reservoirs of the Middle East.

Total has longstanding expertise in the area of EOR. As early as the 1980s, spurred by surging oil prices after the oil shocks of 1973 and 1979, the Group committed a significant part of its R&D effort to this field, with success. Those pioneering studies enabled Total to test a wide range of chemical, thermal and miscible-gas injection processes to create a solid portfolio of expertise. Several of the Group’s pilot projects became benchmarks for the oil industry: in France, polymer flooding on an industrial scale; in the Republic of Congo, the first offshore steam drive pilot. For Exploration & Production teams from the laboratory to the field, it was a decade of substantial investment. But when oil prices tumbled from an average of $86 in 1980 to a mere $16 in 1998, the high cost of the additional barrels extracted using these new technologies quickly became prohibitive.

In 2003, although crude prices remained relatively low, Total’s E&P branch again turned its attention to EOR and decided that its know-how, which market pressure had pushed into the background, should again be brought to the fore and developed as a hub of leading-edge expertise. Studies got under way to achieve a world first by developing a polymer injection pilot in the deep offshore. The 2006 establishment of a specific R&D program at the Scientific and Technical Center (CSTJF) in Pau [southwest France] confirmed the reinstatement of EOR as a key strategic priority. Reaching across organizational boundaries to capitalize on synergies within the Group (particularly with the Petrochemicals unit), this multidisciplinary project is backed by extensive laboratory resources. It aims to develop processes suitable for Total’s portfolio of assets, consisting largely of offshore acreage, as well as for optimizing production from the carbonate reservoirs of the Middle East, where most of the world’s liquids potential is located.
Total’s involvement in EOR projects

*SAgD: Steam Assisted Gravity Drainage. **WAg: Water Alternating Gas.

1. Drilling on the Dalia field, Angola.
2. The Abu Al Bukoosh platform, in the UAE.
3. Boiler plant at Lacq, France.
The EOR program initiated by Total's R&D in 2006 attests to the strategic emphasis that Total is placing on this field. Numerous technical options are available such as injections of chemicals, CO₂, steam or water under controlled salinity. The diversity of these techniques matches that of the target reservoirs. From the most basic research to the most daring pilot installations, every field of expertise is being mobilized.
The aim of the EOR project is to scale up innovations and develop field pilots as quickly as possible. Project architecture is underpinned by the integration of expertise from the laboratory to the field and by synergies with the worldwide research centers of the E&P branch, and with the Group’s Petrochemicals unit.

Naturally, the oil industry did not wait for the threat of peak oil to address the crucial issue of increasing hydrocarbon recovery: water flooding, the oldest technique, was first applied in the late 19th century and remains the most widely used method today. Water flooding and the injection of immiscible hydrocarbon gas are known as “secondary recovery” techniques because they are often implemented after the initial (or primary) recovery phase, which utilizes natural drive from the wells. Secondary recovery is a pressure-maintenance strategy aimed at postponing oilfield decline and displacing mobile oil toward the production wells.

THE CHALLENGES OF TERTIARY RECOVERY

In laboratory conditions, water flooding yields recovery factors of up to 70 or even 80% of the original oil in place in a core sample, but that figure drops to an average of 32% in field conditions, due to reservoir heterogeneities. It also varies considerably with the viscosity of the target oil. Although recovery factors can be as high as 40% to 50% for a light oil, the figure falls to a mere 10% when oil viscosity is on the order of a hundred centipoise (cP). Advanced EOR techniques able to overcome the limits of secondary recovery...
are thus in the realm of so-called “tertiary” recovery processes. With the exception of certain gases (CO₂, H₂S and miscible hydrocarbon gas), tertiary recovery methods inject substances not normally found in oil reservoirs, such as chemicals, solvents, steam, air, low-salinity water and bacteria. All these processes aim to improve drainage by optimizing the macroscopic sweep of mobile oil; at the microscopic level, they are also designed to trigger physical-chemical reactions to displace any residual oil trapped in the matrix and resistant to conventional recovery methods. Potentially applicable to all conventional oilfields regardless of their stage of maturity, these technologies are most eagerly awaited for application to reservoirs with low permeability or containing viscous oil — the cases in which enhancing productivity and recovery factors poses the greatest challenges.

INTEGRATED KNOW-HOW

The scope of research for improving oil recovery is split between the EOR project for conventional oils with viscosity of up to 1,000 cP, and the Extra-Heavy Oil project, both of which are run by R&D at the CSTJF. A number of bridges are in place between the two entities, since the line between the two areas is blurry for some process categories, notably thermal recovery techniques.

The multidisciplinary teams in place to develop enhanced recovery span the full chain of expertise, from the reservoir to the surface and from the laboratory to petroleum architecture and field operations. As for all teams dedicated to ensuring the growth of oil production, these experts face the task of transforming laboratory innovations efficiently into operational field pilots. The teams can avail themselves of world-class laboratory resources such as the laboratories of Physical Chemistry and porous media at the Mont/Lacq petrochemicals R&D hub (PRDML) and the Petrophysics laboratory of the CSTJF, both in southwestern France. They also collaborate with the international research entities of the E&P industry, namely the Stavanger Research Center (Norway); E&P Research and Technology Center in Houston (United States), the Total Research Center in Doha (Qatar) and the Aberdeen Geoscience Research Center (United Kingdom). These far-flung skills and resources are held together and coordinated through the organization of this extensive project as a fully-integrated hub of skills. For it is only by bringing Total’s myriad areas of expertise into play that recovery factors can be pushed to their uppermost limits. The stakes of the challenge must not be underestimated: every percentage point of additional recovery will yield a “bonus” equal to four years’ worth of global production at the current rate.
**What is mobility?**

A fluid’s mobility is defined as the ratio of its relative permeability in a porous medium to its viscosity. Viscosifying water by adding polymers aims to achieve a mobility ratio of 1 between water and oil—i.e., in other words, the same mobility for the two fluids. In water with low salinity, a polymer concentration of 300 parts per million (ppm) or 0.3 g/l can easily boost the viscosity of water by a factor of 10.

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**THE PROMISE OF CHEMICAL EOR**

The use of polymers and surfactants to improve the efficiency of water flooding is currently a major focus of investigation within the framework of the EOR project. This option turns out to be particularly well-suited to Total’s portfolio of assets. Supported by extensive laboratory resources, these techniques will be evaluated on a pilot scale in the near future. A world premiere is in the making, the hallmark of Total’s bold innovative capabilities.

Chemical-based enhanced oil recovery primarily targets argillaceous sandstone reservoirs containing oil with viscosity of less than 50 cP. Potentially well-suited to the conventional acreage in Total’s portfolio, most of which is offshore, chemical methods are a major focus of the Group’s R&D efforts in the field of EOR. The process of qualifying polymers and surfactants able to boost production and recovery calls for synergy between the E&P branch and Total Petrochemicals France, to capitalize on all the know-how and research resources available.

**POLYMERS, THE KEY TO ACCELERATED RECOVERY**

It’s a simple fact: in downhole conditions, water is almost always less viscous than oil. Ideally, however, in addition to maintaining reservoir pressure, injected water should be able to push the oil, like a piston. Yet because it flows more easily than the oil, the water flood often fails to fulfill this function, escaping through the paths of least resistance that it finds in the reservoir (see box). In theory, the solution is as simple as the problem itself: simply reduce the mobility of the water by increasing its viscosity and making its properties as close as possible to those of the target oil. This can be achieved by adding polymer to the water. Polymers are long chains of molecules in which the same basic block is repeated many times. Provided the polymer is water-soluble, it can “uncoil” in the water to raise its viscosity. The “piston effect” thus becomes much more efficient, potentially increasing the recovery factor by 5 to 15%.

**A BENCHMARK INDUSTRIAL EXPERIMENT**

Total has long demonstrated the tremendous potential of using polymer additives to control the mobility of water. In 1977, the Group began its first pilot program in the Châteaurenard oilfield, a shallow, argillaceous sandstone reservoir in the southern part of the Paris basin. Consisting of highly permeable unconsolidated sand and characterized by a temperature of 30°C, this reservoir contains a viscous oil (40 cP in reservoir conditions). The pilot entailed one injection well and seven producers. Operated until the mid-1980s, the installation achieved excellent results on four of the producing wells, and justified the industrial deployment of polymer injections on Courtenay, a mature...
Comparison of sweep efficiency: water versus polymer

A DEEPWATER FIRST

Today, Total’s EOR experts are facing an even greater challenge and aiming to achieve another world first: polymer flooding in the extreme conditions of the deep offshore. This time, sights are set on Dalia, the immense

Results of a polymer injection on Courtenay

satellite field also containing viscous oil (40 cP) where the water cut had reached 80%. After the initial pilot phase undertaken in 1985, this second program was deployed on an industrial scale from 1989 with four injection wells and sixteen producers. The viscosity of the injection water (420 m³/d) was increased to 23 cP by the addition of a polyacrylamide polymer at a concentration of 900 ppm for the first twenty-seven months of development, then gradually lowered to 100 ppm over the ensuing two years. The project offered ample proof of the effectiveness of the process: 56,700 m³ of additional reserves were produced, a 9% improvement over the initial recovery factor of 22%. Highly conclusive for a target oil of this viscosity, the Courtenay industrial pilot still stands as a global benchmark for this technology.
A number of factors make deep offshore reservoirs excellent candidates for polymer flooding: they are generally buried at relatively shallow depths beneath the seabed with fairly moderate temperatures and relatively viscous oils. Moreover, water flooding is already the recovery method most commonly implemented for such fields.

The launch of this project in 2003, three years before Dalia came on stream, marked a decisive turning point in Total’s strategy: EOR methods would no longer be confined to mature oilfields, but also would be applied whenever appropriate on new acreage.

Operations began in late 2008 with in situ testing of viscosified water injectivity. The fact that it took five full years to reach the field testing stage is indicative of the scale of the multidisciplinary study needed to demonstrate the feasibility and cost-effectiveness of the technique. Four main objectives were targeted by the study, entailing a combination of expertise in geosciences, chemistry and petroleum architecture:

- selection of a polymer appropriate for the Dalia reservoir and oil, via a dedicated laboratory program;
- estimation of the additional resources potentially recoverable by viscosification of the injection water, and analysis of various strategies based on extensive reservoir modeling using parameters acquired in the laboratory;
- definition of the objectives and design of a pilot installation;
- logistics and study/assessment of the additional operating equipment needed to implement the process on the Dalia field.

THE CHALLENGE OF SALINITY

It is important to find the right polymer for each field. Salinity, temperature, composition and properties of the oil, the fluid dynamics at play in the reservoir, are among the parameters guiding the choice of the appropriate molecular linkages. Although polymers can easily accommodate temperatures of 70 or even 80°C, they lose their viscosifying power in highly saline water: the long, flexible polymer chains are effective only when uncoiled, and salt has the effect of “tangling” them. Accordingly, improving their behavior in the presence of salt is a major focus of research.

Candidate molecules include what are known as biopolymers, produced by yeasts or bacteria. Polysaccharides are one topic of interest: these molecules have excellent solubility and a rigid structure able to resist salt. Another key advantage is that they can accommodate temperatures of 100 or even 110°C. Despite their promise for high-temperature, high-salinity reservoirs, they have one major limitation: as bio-products generated by bacteria, they are highly biodegradable. It is imperative to counter biodegradation and keep the polymer stable in the presence of reservoir bacteria.
In production since 2006, Dalia ranks among the world’s most extensive deepwater developments. The numbers speak for themselves: 230 km² of oilfield, 4 reservoirs and 71 subsea wells, consisting of 37 producers, 31 water injectors and 3 gas injectors. Polymer injections for this colossal development, scheduled to begin around 2013, should translate to an average of 5% incremental reserves over twenty years, following at least three years of conventional water flooding. The selected polyacrylamide, with a molecular weight of 18 million dalton, was qualified with respect to its solubility (quick and homogeneous), its viscosifying power over a broad salinity range (25 to 52 g/l); its shear strength when flowing through the chokes and valves of the injection wells; its ability to remain stable during the years it spends in the reservoir before reaching the production wells 500 to 1,500 m from the injectors; and the feasibility of injection. Other significant parameters, such as price and availability, were taken into consideration as well.

Field characteristics
- Reservoir temperature: 50°C
- Average permeability: 1 D
- Oil viscosity in reservoir conditions: 3 to 7 cP
- Water viscosity in reservoir conditions: 0.5 cP
- Salinity of formation water: 130 g/l
- Maximum water injection volume: 375,000 b/d via 4 injection lines totaling 35 kilometers in length
- Average water injection volume per well: 12,500 b/d

Phased development
December 2008-January 2009: injectivity test on one well using 60 T of polymer in powder form.
2009: launch of a pilot project for at least one year on an injection line supplying three injection wells, entailing daily consumption of 5 to 6 T of polymers.
2013: deployment of the process to the entire field, involving the injection of 40 to 50 T of polymer per day.
Surfactants make up the second class of molecules being implemented for chemical EOR processes. Unlike polymers, which merely accelerate recovery by optimizing the drainage of mobile oil, surfactants target a true improvement in performance. They have the ability to displace the immobile fraction — the so-called “residual” oil — trapped in the reservoir; they offer potential increases of 20 to 40% in recovered quantities.

Like soaps, surfactant molecules have a hydrophilic head and a lipophilic tail. This property causes them to move to the interface between oil and water, thereby diminishing the interfacial tension (see box) and resulting in the formation of a microemulsion, a stable mixture of oil and water. In practice, however, surfactants are limited by their tendency to be adsorbed on the surface of the reservoir rock as they advance through the formation. To limit this phenomenon, alkalis must be added to the aqueous solution that is injected into the well. These molecules of basic pH raise the negative charge on the surface of the rock and repel the surfactants, which are also negatively charged.

**TAILOR-MADE SURFACTANTS**

There are many different families of surfactants, presenting a wide range of molecular arrangements. The challenge for EOR applications consists of finding the right formulation giving the best match with the characteristics of the candidate field (water quality, salinity, pH, composition of the oil, temperature, etc.). Finding the solution demands a fundamental knowledge of the relationship between the surfactant’s structure and its properties. The aim is to achieve the strongest possible interactions, of equal energy, between the tail of the surfactant and the oil, and between the head of the surfactant and the water. As for the resulting microemulsion, it must be as voluminous as possible yet remain fluid. Therefore, it must not contain microgels, which could develop due to the spatial arrangement of the surfactants at the oil/water interface. In some cases, it is necessary to understand and control the behavior of a mixture of two different surfactants.

Conducted in close cooperation with the chemicals industry, research into new formulations is being carried out by a team from Total Petrochemicals France. Working on behalf of the EOR project at the Lacq laboratories (southwest France), they are relying on the experience and physical chemistry know-how acquired during the development of the microemulsion industrial pilot for the Châteaurenard oilfield (see box).

**A PILOT PROJECT IN THE MAKING**

Today, the teams are working on the definition of a new pilot. This five-spot unit (an injection well at the center of a square measuring 100 m per side, with four producing wells near the corners) will be installed in a large mature oilfield offshore. The pilot will target unconsolidated reservoirs.
Deforming oil droplets

All systems tend to take the form that consumes the least energy. In an oil/water system, the energy level is highest at the interface, so the oil takes a spherical form in order to limit this contact surface. However, oil molecules located at the periphery of the droplet are destabilized by their contiguity with water molecules and seek to penetrate inside the droplet to re-equilibrate. This generates capillary pressure, which prevents deformation of the droplet. To extract a droplet of oil trapped in the porous network of a reservoir by means of water flooding, the droplet must be pushed through smaller pore thresholds – in other words, it must be deformed. This is where surfactants come into play: they diminish the interfacial tension, lower the capillary pressure and allow the droplet to deform.

Doped oil recovery at Châteaurenard

From 1983 to 1985, the microemulsion industrial pilot on the Châteaurenard field (southern part of the Paris basin) demonstrated the extraordinary potential of surfactants in the case of a viscous oil (40 cP). Before the start of the pilot program, the recovery factor of the field stood at 40% with a water cut of 90%. The sandstone reservoirs, buried at a depth of 600 meters, exhibited good permeability and low salinity. In a configuration consisting of four injection wells and nine producing wells, the pilot injected a microemulsion (oil, surfactants, water) prepared at the surface, followed by a polymer slug. Upon completion of the program, the final recovery factor had increased by 27 points to reach nearly 70%. Given the high viscosity of the target oil, this was a remarkable achievement.

THE CHALLENGE OF CARBONATES

Carbonate reservoirs like those typical of the Middle East pose greater challenges in terms of chemical-based EOR processes. Since this region is estimated to hold nearly 60% of the conventional oil reserves yet to be produced, it is a pillar of future strategy and a crucial focus of R&D. Two major issues must be resolved to adapt chemical processes for the specific characteristics of carbonate reservoirs, and Total’s R&D has made this one of its priorities. One problem is the tremendous heterogeneity of the carbonate layers, coupled with lower permeability and often with the presence of complex fracture networks. In this type of rock, injected water can channel through the fracture network and end up being produced without efficiently sweeping the matrix as a whole. The second problem relates to the strong affinity between carbonates and the chemicals used. In a carbonate environment, the chemicals have a greater tendency to adhere to the rock than is the case in argillaceous sandstone formations leading to excessive chemical consumption. Moreover, if the surfactants are adsorbed onto the first centimeter of rock they encounter, they certainly will not penetrate far enough into the matrix.

Deforming oil droplets

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At Total, all of the R&D projects in the area of EOR, from physical chemistry to the testing of processes on core samples under reservoir conditions, are carried out by a group of dedicated laboratories.

At Lacq, teams in the laboratories of the Mont/Lacq R&D hub of Total Petrochemicals France (known by its French acronym, PRDML) are working on qualifying surfactants and polymers for each field that is a candidate for chemical-based EOR. This initial step in the sequence of studies involves the use of dead oil and small artificial cores that replicate the characteristics of the target reservoirs. The polymer properties are first analyzed in the absence of oil in a laboratory specializing in polymers and surfactants. The qualification process for these molecules is a veritable marathon, involving dissolution tests, the definition of dissolution protocols, studies of degradation, temperature sensitivity, and other parameters. A physical chemistry laboratory is dedicated to screening and qualifying surfactants with the goal of selecting the optimal chemical system for a given oil — “optimal” being defined as the one that will lead to the lowest interfacial tension. To determine the best choice based on the different physical-chemical parameters (e.g., pH, salinity), various mixtures of water, dead oil brought in from the fields and surfactants are prepared in test tubes, placed in ovens and heated to reservoir temperature for several days. The impact of the disruption caused by dissolved gases is then studied in a sapphire cell under a pressure of up to 400 bar. The final phase of studies conducted at the PRDML laboratories focuses...
on sweep efficiency in a porous medium. The test columns are sandstone cores 35 cm long, which are first saturated with oil and swept with water. They then undergo flooding with surfactant and polymer slugs in cells under a pressure of 4 bar. Eight test benches are dedicated to evaluating the impact of these chemicals on the final recovery of residual oil in various scenarios (size and concentration of the slugs). Thanks to the limited scale of this purpose-built experimental arrangement, the test can be completed in just two weeks. Once the appropriate chemicals have been selected by the Lacq laboratory teams, the experts at the Scientific and Technical Center (CSTJF) of the E&P branch in Pau move into action. Their role is to study recovery mechanisms. This time, the tests are performed at the temperature and pressure conditions of the reservoirs on actual core samples from the fields, rather than on analogues. The CSTJF is where the chemicals undergo their final qualification testing, but the full spectrum of EOR processes is tested there as well (flooding with CO₂, air, steam, water-alternating-gas injections, etc.). Each study takes several months — a timescale entirely different from the one at Lacq.

1. A laboratory technician at the Mont/Lacq petrochemicals R&D hub.
2. Observing the phase behavior of a water/surfactant/alkane system.
3. Incidence of gas pressure on the physical-chemical behavior of a mixture of crude oil and an aqueous surfactant solution.
5. Apparatus for testing rock samples swept with water or hydrocarbons.
Easily miscible with light oils, CO₂ seems like a viable alternative to hydrocarbon gas injections. This process will likely be an important component of growth in oil recovery in the future, for both economic and environmental reasons. At Total, a number of R&D studies are under way to ensure complete mastery of the technology.

Total has several reasons to keep its sights set on CO₂. First, through its historic leadership in the production of very sour and acid gas deposits, the Group has developed a wide range of solutions for treating this gas. Its Sprex® CO₂ process is one example of an innovative and cost-effective technology for separating the CO₂ stream from highly carbonated gases. Second, the Group’s commitment to combat climate change has led it to rank emissions of greenhouse gases (GHG), especially CO₂, among its major concerns, giving rise to a particularly dynamic R&D program in this area. The construction of a demonstrator pilot to capture CO₂ released by combustion and sequester it in geological formations attests to this strategic emphasis. Built near the Lacq gas fields, the unit marks the first time in Europe that a depleted onshore hydrocarbon reservoir has been selected as a storage site. Because it is also the first pilot project in the world to focus on CO₂ from combustion, it is a key milestone toward the large-scale deployment of this innovative technology.

**Surface facilities and an integrated approach for an EOR**

**CO₂ capture**
- Source of the gas:
  - Thermal power plants
  - Ethanol and fertilizer production
  - Natural sources
  - Oilfield associated gases
  - CO₂ purity

**Transport**
- Gas characteristics
- Compression
- Thermodynamics
- Pipeline design

**Injection**
- Wellhead and bottomhole pressure and temperature
- Injectivity
- Environment:
  - onshore
  - offshore
  - subsea

**Expertise involved:** Surface installations / Well engineering / Reservoir engineering / Economics
Asphaltene deposition

CO₂ injection in hydrocarbon reservoirs occasionally leads to unexpected multiphase behavior and asphaltene deposition that can hinder production. Total has developed a dedicated mercury-free PVT (pressure-volume-temperature) apparatus for CO₂ injection studies. In order to avoid misleading interpretations of PVT measurements, an optical cell is used for preliminary screening by visual observation. These photos show the results obtained on a 32 API oil at 132°C. The initial bubblepoint of the oil is 273 bar and the reservoir pressure is 480 bar. The amount of CO₂ added to the reservoir fluid is 1.4 mole/mole. During the depletion process, a heavy asphaltene phase is observed to separate out from the fluid when the latter is in the critical state, with formation of a gas phase and two liquid phases (asphaltenes and condensates). These phases ultimately become miscible as the liquid becomes lighter. In atmospheric conditions, the liquid is perfectly homogeneous and stable.

EOR AND GHG EMISSIONS ABATEMENT

Total’s expertise in both of these areas is currently being put to use to advance studies on the potential of CO₂ flooding for enhanced oil recovery. Due to its thermodynamic behavior — the gas is often in the supercritical state and miscible in reservoir conditions — CO₂ indeed holds promise as an alternative to hydrocarbon gases, which could be monetized instead, especially for the recovery of light oils. Furthermore, the CO₂ option seems consistent with the Group’s goal of “virtuous” industrial management of the gas as a component of GHG emissions control, an issue that is especially crucial given the prospects for future production of highly acid gases in the Middle East. Accordingly, Total is now investigating the possibility of incorporating CO₂ injections for EOR as an intermediate phase in the complete industrial process of CO₂ capture and storage now being demonstrated at Lacq.
CO₂ FLOODING OFFSHORE

CO₂ flooding is arguably an appealing option, because it not only meets the requirements of EOR, but at the same time offers a means of storing the gas in the reservoir. This is the option that Total’s EOR teams have selected in connection with a project being evaluated for the North Sea, which may be implemented around 2016. The aim is to replace the hydrocarbon gas produced by the field with CO₂ in order to maintain pressure in the reservoir, which contains gas-condensate and has currently entered the phase of rapid decline. Pressure maintenance is necessary to prevent some of the condensates from settling in the reservoir, which would lead to a loss of recovery. Reinjecting the gas produced from the field was ruled out for economic reasons (methane being a marketable product), but the CO₂ alternative is worth considering. Access to a potential source of CO₂ is now possible thanks to the British government’s program to...
promote CO₂ capture technology. Technical studies undertaken in 2007 and lasting one year analyzed the entire chain of surface operations involved in the process: transport to the platform (thermodynamic behavior in the pipeline); installations and procedures required to ensure the right pressure and temperature for downhole injections; dedicated facilities for separating and recycling the resulting additional volumes of CO₂; and finally, storage in the reservoir.

In addition, Total’s specialists have been closely involved in studies on the thermodynamic behavior of the CO₂, specifically concerning the CO₂/oil equilibriums. This research will serve in the development of a future EOR pilot planned for 2020. The key challenge here is to predict the effects of CO₂ injection on a huge chalky reservoir subject to a significant subsidence phenomenon.

LOOKING EASTWARD

Naturally, it is in the East, Middle and Far East that CO₂ should provide the best leverage for improving recovery factors in the future, for it is these regions that harbor the largest volume of acid and sour gas resources (CO₂ and H₂S). One prerequisite for successful implementation is the presence of an economical source of CO₂ near the candidate fields. Total’s EOR teams are already at work studying the feasibility of the offshore Abu Al Bukoosh field operated by the Group in Abu Dhabi (UAE). On the agenda are the qualification of the CO₂/oil equilibrium and its integration into a dynamic reservoir model in order to assess the effectiveness of various CO₂ injection strategies. This option, which would replace water flooding then hydrocarbon gas flooding, would serve as a demonstration within the framework of a mature field with a current water cut of about 90%.
Of the broad spectrum of options highlighted by its research, Total is focusing in particular on two main avenues. One is the thermal route, already applied extensively for extra-heavy oil production but to date only to a limited extent for conventional oils. The other is an option that has recently come to the fore, which consists of modifying the injection water salinity. Both areas are among the possible keys to enhanced recovery in carbonate reservoirs.

While chemical flooding and CO₂ injection have emerged as the two likely pillars of an enhanced recovery strategy, these processes are far from being the only possible solutions. There is a long list of other options which include fire flooding, injection of softened water, microbial flooding, alternate or simultaneous water and gas flooding, nitrogen flooding and flue gas injection. Some of these technologies are well documented but have had limited application due to the high cost of the additional barrels produced. Others, discovered more recently, have yet to be qualified. Ruling out not a single one of these options, Total’s EOR research efforts are directed primarily at technologies suitable for carbonate reservoirs, which constitute the most challenging targets in terms of enhanced recovery.

STEAM FLOODING IN CARBONATE RESERVOIRS

Total’s achievements in thermal production methods during the 1980s rank among the industry’s most outstanding examples. Of the four pilot programs operated between 1977 and 1988 (Lacq Supérieur and Saint-Jean-de-Marvejols in France, Poso Creek in California and Émeraude in the Republic of Congo), two were world premieres and to date remain the only such projects ever carried out in fractured carbonate structures — with the additional challenge of an offshore context for Émeraude. The first steam drive project took place from 1977 through the end of the 1980s on the Lacq supérieur reservoir, a highly heterogeneous structure consisting of porous calcareous rock with low permeability alternating with dolomites of low porosity but high permeability through the fracture network. Initially undertaken with a single pilot and extended two successive times to reach a total of four injection wells (one of which horizontal) and twenty producing wells, this program showed the method to be effective in this type of environment, achieving an overall incremental production estimated at 110,000 m³ by 1987. Moreover, the program revealed a significant secondary phenomenon: the ionic dissolution of the carbonate under the action of the steam, resulting in significant production of CO₂ inside the reservoir. This CO₂ further contributed to additional recovery.

The same phenomenon was observed on the steam flooding pilot implemented from 1985 through 1988 on Émeraude, a field offshore Congo that was very difficult to produce. This extremely bold project deployed over
Steam flooding techniques

three reservoir horizons required drilling from a tilt rig to drive the deviated wells (two five-spot wells for steam drive injections in two reservoir horizons and one cyclic steam injection or “Huff & Puff” well in the third horizon). The reservoirs are buried at a mere 200 m under the sea floor. The results were mediocre on two horizons, but very encouraging on the third. Oil production was increased from an initial 20 m³/d to 100 m³/d with cumulative production of 491,000 barrels over three years. The recovery factor is estimated at 50%, an impressive feat on a field where it had been stagnating at a mere 3%.

A new pilot is being investigated for an African oil field in order to assess the technological, economic and environmental performance of various thermal production options, including downhole steam generation.

PLAIN OLD WATER
Water flooding may actually prove to be a promising solution for boosting recovery factors in carbonate reservoirs. Despite the industry’s longstanding use of this method, some recent discoveries have shed significant new light on the process mechanisms. In the course of research on the Ekofisk field (Norway), it became apparent that the saline composition of the injection water had a significant incidence on the recovery factor. Laboratory samples have indicated that recovery can range from 10 to 50% depending on the type of ions contained in the water (calcium, sulfate, magnesium, etc.). In sandstone reservoirs, the key parameter is the total salt concentration of the injection water—specifically, the lower the better. Incremental recovery varies from 2 to 30% depending on the salt concentrations, with an average of 10% in unfractured rock. This important topic is the focus of research by Total’s petrophysics experts, in collaboration with several American, French and Norwegian universities. Studies aim to gain an understanding of the fundamental mechanisms at play in order to move to the pilot stage as quickly as possible.
Present in more than one hundred thirty countries, Total is one of the most dynamic players in the global oil and gas industry, with a number of truly major technological and economic achievements to its credit.

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In addition to its prominent positions in oil and gas exploration and production, gas and power, renewable energies, trading and transmission, and refining and marketing, Total is a key player in the Chemicals sector. In 2008, the Group produced a total of 2.34 million barrels of oil equivalent per day (Mboe/d).

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