



CO2 for Enhanced Oil Recovery

During the lifetime of an oil reservoir, oil production is usually implemented in two or, if economical, three phases. The primary phase is categorized by the natural flow of crude oil to the producer wells. However this is often quickly supplemented by a secondary induced oil recovery (IOR) phase which augments oil production through a variety of different technologies.

Each reservoir will respond individually (i.e. there are no standard figures that can be quoted), however one may indicate that primary production will typically result in the recovery of between 15-25% of the original oil in place (OOIP), while secondary IOR using conventional techniques will recover between 20-40% of the OOIP.

With more recent advances in drilling and reservoir technology, the anticipated recovery for the maturing North Sea Continental Shelf (NSCS) is now estimated to lie on average between 45-50% of OOIP. Values above 60% are very rare, although Shell indicate that for one of their off-shore fields, Draugen in the Norwegian Sea, they were predicting recovery of 64% OOIP with a possible 75% using a miscible gas such as CO₂.

The Permian Basin is one of America's premier energy provinces. The basin covers southeast New Mexico and much of western Texas. It has produced 30 billion barrels of oil and currently produces 900,000 barrels per day or about one-fifth of total U.S. oil production.

The vast majority of the large reservoirs in the Basin are in carbonates producing from depths between 3000 and 7000 feet below surface. The predominant primary recovery mechanism was solution-gas drive. The reservoirs have been extensively waterflooded. Expected recoveries after waterflood range from 30 to 45 percent of the original oil-in-place (OOIP).

From early on, the large reservoirs in the Basin were considered to be excellent candidates for miscible flooding using CO₂ injection. This is due to the factors mentioned in the previous paragraph, plus a low geothermal gradient in the area that results in lower pressure required for miscibility for a given crude. Another factor was the relatively high residual oil saturation after waterflooding.

In the early 1970's, Chevron developed a plan for the first miscible CO₂ flood in the Permian Basin, at the SACROC Unit. The SACROC Unit covers 50,000 acres and was formed to optimize secondary and tertiary recovery of oil in the Canyon Reef, a Pennsylvanian age reservoir. The reef has an average porosity of 4% and mean permeability of 19 millidarcies. It initially had 3 billion barrels of oil in place and has recovered 1.4 billion barrels to date.

Over 1000 wells have been drilled in the Unit, and typical well spacing is 20 acres (8 hectares). Currently there are over 200 wells producing. Chevron recovered CO₂ from produced gas streams at four gas plants in the southern part of the Basin, and dehydrated and transported the gas 220 miles to SACROC for injection. Injection was initiated in the Unit in January 1972 on a limited basis.

Oil production in response to CO₂ injection began soon after peak waterflood production response occurred. Therefore, it is difficult to determine the impact of CO₂ injection by simply looking at the Unit total production curve. Review of individual pattern curves indicated that the project was technically successful from an oil recovery standpoint. There were operational problems such as corrosion and scale but these problems were managed and did not severely impact project economics. However, several factors existed that contributed to the project not being as economically successful as it could have been.

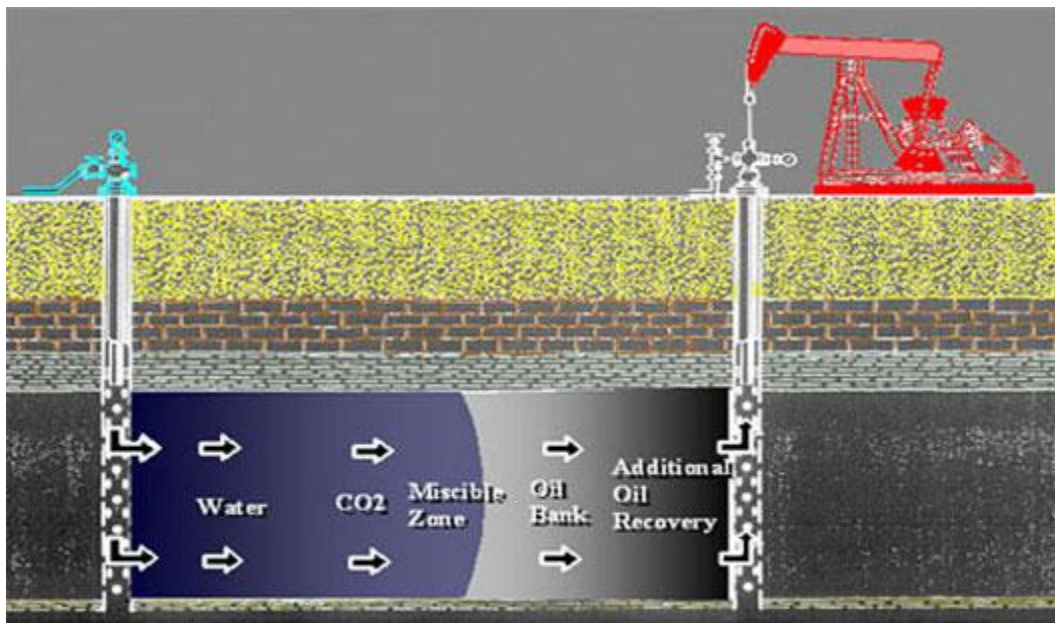
This was the first large scale flood and there was a steep learning curve. Chevron did some excellent work but they were on the cutting edge and mistakes were made. There was

insufficient CO2 supply to flood the entire field in a reasonable time frame, so areas of the field had to be prioritized for miscible processing. Chevron's reservoir management philosophy at that time was to focus on areas where waterflood recovery was poor and therefore had the highest percent of original-oil-in-place remaining in the ground. Years of experience with this and later floods by many operators developed an industry consensus that the areas with the best waterflood performance would perform best under CO2 flood. The higher amount of oil remaining in the formation in some areas was of little use if the injectant never contacted it, and the reason for performance variation was found to be variations in well-to-well connectivity and not variation in residual oil saturation at the pore level.

Chevron also experimented with many different injection schemes. Many of these schemes called for far less than optimum CO2 slug sizes. In some cases, CO2 injection was ended soon after initial production response occurred. Returning to water injection at that point severely depressed the amount of incremental oil recovered.

Lastly, operation of a CO2 flood requires strict discipline in reservoir management. Chevron was limited by their initially installed gas handling capacity and would not spend the capital to increase that capacity. This in turn caused them to curtail CO2 injection so as not to produce more gas than could be handled. This delayed future expansions until the 1986 oil price crash rendered those future expansions much less economically attractive, and at that point a combination of personnel turnover and loss of status for the project within the company resulted in stagnation. In 1992 Chevron sold the SACROC Unit to Pennzoil. In turn, Pennzoil was bought by Devon in 1999. Devon continued forward with some expansions that Pennzoil's staff had recommended, but they decided that they did not want to be in the CO2 flooding business, so in April 2000 they sold the Unit to Kinder Morgan CO2 Company (KMCO2).

In general it is acknowledged that using CO2 for tertiary EOR may add an additional 5-12% of OOIP to the anticipated total production. The mechanism by which this occurs is perhaps best illustrated in the sketch below showing the classic configuration of an injector-well working in combination with a producer.



The CO2 is typically injected in an alternating water and gas (WAG) process. As illustrated above, the water is being injected behind a "slug" of CO2 that creates a miscible zone which helps release oil that had previously been trapped when using only water.

At the Kinder Morgan SACROC Unit this process has been in operation since 1972. A typical injection well is shown in the photograph below where the wellhead is on the left of the image and the two pipes on the right are for the water and the CO2 supply lines.



The frequency of alternating the working fluid in a WAG process can vary considerably from a few days to several months: it very much depends on the oil reservoir, injection and production volumes, well location and residual oil. A useful rule-of-thumb is based upon when the the volume of breakthrough gas or water-cut suddenly increases compared with the volume oil that is produced.

The producing wells are somewhat similar in appearance as shown in the adjacent photograph. In practice whenever the terrain allows, these injector / producers configurations are spread out in a rectangular array with 1 - 2 km spacing between each.

A key concern regarding early operations of these wellheads was the issue of corrosion. However the experience from West Texas shows that one originally had a tendency to over specify the material properties of the wells and piping. In practice stainless steel is employed, but not extensively and only in critical areas. However one does rely on injecting smaller volumes of chemical inhibitors that protect the metal surfaces wherever there is the corrosive mixture of water and CO2. You can read more about corrosion mitigation measures [here](#).

A group of producer wellheads are linked together to a larger field pre-processing unit as shown in the photograph below. Here the collecting manifold from the producer wells is observed to the left in the image, while the three pressure tanks separate the water, oil, and gas with CO2, before pumping to a centralized processing plant.



An essential feature of using CO₂ for EOR is that the CO₂ will mix and remerge with the produced oil and gas. At SACROC separation and re-injection of the CO₂ is all handled at a central Reprocessing Plant located near the town of Snyder. The complete Snyder Facility is literally a mausoleum covering the state of the art in CO₂-stripping since the early-70's.

The extent by which the technology has evolved during this time, is perhaps best illustrated by the photograph below showing the complete expanse of the Facility as seen from a distance. The columns in the middle are part of the long-closed potassium plant that was originally used.



Today's amine and membrane facilities are located on the right of the image. And part the latest unit being brought into operations by KMCO₂ for their SACROC reprocessing is shown in the photograph below.



This is part of the overall \$1 billion investment that KMC02 are currently making in order to be able to inject 5-8 mtCO₂/yr for EOR into their SACROC Unit within 2004. SACROC will therefore continue to be the world largest CO₂-flood.

With acknowledgment from <http://www.co2.no/>