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Use of Carbon Dioxide in Enhanced Oil Recovery

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Summary. Large volumes of oil will remain in U.S. oil reservoirs when standard recovery methods have been completed. Supercritical carbon dioxide can be used to recover part of that remaining oil. If carbon dioxide is dense enough, it extracts hydrocarbons from the oil to make a mixture miscible with crude oil. Such a mixture can recover 95 percent of the oil in controlled laboratory flow settings. Heterogeneity of reservoir rocks and the low viscosity of carbon dioxide reduce the fraction of oil recovered in projects to lower but still significant levels. With the construction of three pipelines to carry naturally occurring carbon dioxide from Colorado and New Mexico to Permian basin oil fields, large-scale implementation of enhanced oil recovery by carbon dioxide flooding is now beginning.

The use of carbon dioxide for supercritical extraction separation processes (*1*, *2*) and supercritical fluid chromatography (*3*) has received much attention in recent years. A less familiar application of supercritical extraction is the use of high-pressure CO_2 to recover crude oil left behind by conventional methods for recovering oil from porous reservoir rocks. The target for more sophisticated enhanced oil recovery techniques is large. Of the more than 400 billion barrels of oil discovered in the United States, around 300 billion barrels will not be recovered by standard methods. Not all of the oil reservoirs included in that total are suitable for CO_2 flooding or other enhanced oil recovery methods, but there is considerable current effort in the oil industry to implement large-scale CO_2 injection projects. At least as measured by volumes of fluids used, CO_2 flooding will be the largest application of supercritical extraction over the next decade.

Any successful oil recovery technique must overcome the forces that act to trap oil in the pores of reservoir rocks. At discovery, oil in a reservoir will usually flow to the surface unaided, driven by the natural pressure in the formation and by the expansion of gas dissolved in the oil. In a typical light-oil reservoir, primary production, as this simplest of oil recovery techniques is known, recovers only 10 to 20 percent of the oil originally in place. In reservoirs containing heavy, viscous oils, primary recovery may be significantly less. Since the 1940's, secondary recovery methods—injection of gas or water to maintain reservoir pressure and displace oil into producing wells—have been used to recover an additional 20 to 50 percent of the oil in place in light-oil reservoirs. More recently, steam has been injected into heavy-oil reservoirs to heat the oil and reduce its viscosity. In this article, we focus on the use of CO_2 for recovery of light oils, though CO_2 has also been used to reduce the viscosity of heavy oils (*4*).

Until the 1970's, the most important factor in the choice of a secondary recovery fluid was cost. Water and natural gas were used because they were inexpensive and readily available. However, gas is a poor displacing fluid because of its low viscosity; it costs more to compress and inject than water and its fuel value has increased markedly in recent years. Therefore, most secondary oil recovery is carried out by waterflooding, which now accounts for approximately half of the oil production in the United States. Unfortunately, water is not miscible with crude oil, and hence numerous interfaces are present in the reservoir rock as the displacement proceeds. The resulting capillary forces, which arise from oil-water interfacial tensions, trap oil in the very small converging and diverging channels that make up the pore space in reservoir rocks. Enhanced oil recovery processes for light oils are designed to reduce the effects of the capillary forces, which limit the performance of current secondary oil recovery techniques. One way to reduce the magnitude of capillary forces is to reduce the oil-water interfacial tension by adding surfactants—molecules with water-soluble heads and oil-soluble tails—to the injected water. Very low interfacial tensions can be achieved with the right choice of surfactants for a particular crude oil and particular reservoir conditions, and a variety of process designs have been tested in both laboratory and field displacements (*5*).

If interfaces between the injected fluid and the oil could be eliminated entirely, the effects of capillary forces would not arise. Thus, injection of a fluid miscible with oil could eventually recover essentially all of the oil. Unfortunately, solvents that are miscible with crude oil are likely to be hydrocarbons or hydrocarbon mixtures obtained from crude oil in the first place and therefore significantly more valuable than the crude oil displaced. Miscible floods with liquid hydrocarbon solvents are likely to be conducted only in special situations, for instance, where light hydrocarbon liquids such as propane or butane cannot be conveniently transported to market.

While injection of liquid solvents is not economically attractive, in situ genera-

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