Quarterly Technical Progress Report

IMPROVED TECHNIQUES FOR FLUID DIVERSION IN OIL RECOVERY

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OBJECTIVES

This three-year project has two general objectives. The first objective is to compare the effectiveness of gels in fluid diversion with those of other types of processes. Several different types of fluid-diversion processes are being compared, including those using gels, foams, emulsions, and particulates. The ultimate goals of these comparisons are to (1) establish which of these processes is most effective in a given application and (2) determine whether aspects of one process can be combined with those of other processes to improve performance. Analyses are being performed to assess where the various diverting agents will be most effective (e.g., in fractured vs. unfractured wells, deep vs. near-wellbore applications, reservoirs with vs. without crossflow, or injection wells vs. production wells). Experiments are being performed to verify which materials are the most effective in entering and blocking high-permeability zones. Another objective of the project is to identify the mechanisms by which materials (particularly gels) selectively reduce permeability to water more than to oil. In addition to establishing why this occurs, our research attempts to identify materials and conditions that maximize this disproportionate permeability reduction.

SUMMARY OF TECHNICAL PROGRESS

Use of Foams as Blocking Agents. Foams have been investigated extensively as mobility control agents—where sweep efficiency is improved by maximizing the distance of foam penetration into less-permeable, oil-productive zones. Much less work has been performed evaluating foams as blocking agents—where the objective is to maximize penetration and blocking action in high-permeability, watered-out zones while minimizing damage to oil zones. We examined whether the "limiting-capillary-pressure" concept[1] can be exploited to aid placement of foam blocking agents.

Khatib *et al.*[1] applied the concept of limiting capillary pressure to predict foam flow through porous media. To explain this concept, consider two gas bubbles that are flowing through a water-wet porous medium, as shown in Fig. 1. Because of their close proximity, these bubbles are separated by a film of water. A pressure difference, called the capillary pressure, exists between the gas phase and the liquid phase. The limiting-capillary-pressure concept recognizes that if the capillary pressure is too great, water will be sucked away from the film, the film separating the bubbles will collapse, and the bubbles will coalesce. The capillary pressure at which this coalescence occurs is called the limiting capillary pressure. According to Khatib *et al.*[1], this capillary pressure could depend on (1) the type and concentration of surfactant and electrolyte, (2) the gas velocity, and (3) the rock permeability. (Radke *et al.*[2] argue that the limiting capillary pressure is, at best, a very weak function of rock permeability.)

Using the limiting-capillary-pressure concept, one circumstance can be identified where a foam blocking agent could have a placement advantage over a gelant. That is the case where the capillary entry pressure is less than the limiting capillary pressure in the offending high-permeability zone(s) but is greater than the limiting capillary pressure in the less-permeable hydrocarbon-productive zones. (The capillary entry pressure is the injection pressure that must be exceeded to overcome capillary forces and allow the non-wetting phase to enter the porous medium.) In that case, a low-mobility foam will be generated in the high-permeability zone(s) but not in the less-permeable zones. Since no foam is generated in the less-permeable zones, injected fluids will not be inhibited from entering and displacing oil from these zones. In contrast, as long as the foam persists in the high-permeability zones, it will restrict fluid entry. Of course, exploitation of this concept requires identification of the permeability where the limiting capillary pressure equals the capillary entry pressure. Two other limitations must be recognized. First, the injected foam must not undergo a reaction that forms a blocking agent after placement. For example, the surfactant solution must not include a gelant. A low-mobility foam generated in the high-permeability zone(s) will cause the gelant to penetrate an excessive distance into the less-

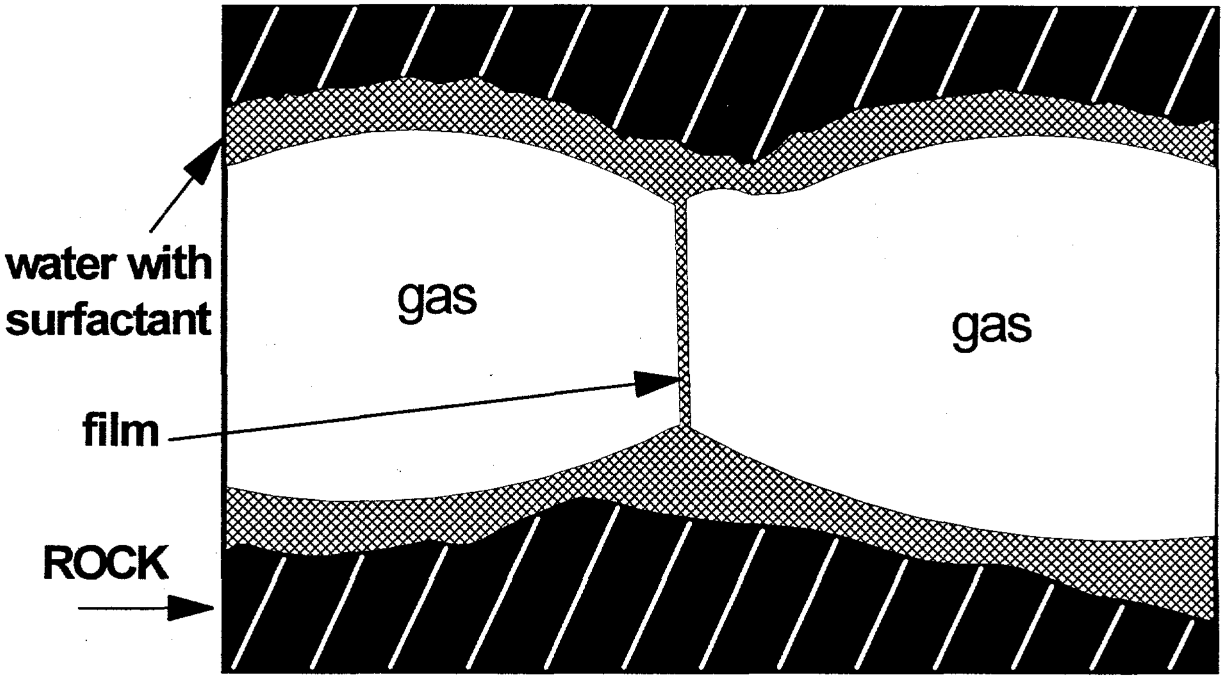

Fig. 1. Concept of Limiting Capillary Pressure.

permeable zones. Second, if water or gas is injected after placement of a foam bank, the foam may eventually be washed out or diminished in effectiveness.

We wish to experimentally verify the concept described above—i.e., using foams to block high-permeability zones without damaging low-permeability zones. This determination required that foam mobilities be measured over a broader range of permeability and fluid velocity than previously reported. The results from our experimental studies were used during numerical analyses to establish whether foams can exhibit placement properties that are superior to those of gelants.

Using a $C_{14\text{-}16}$ α-olefin sulfonate (0.3% Stepan Bio-Terge AS-40 in a brine with 1% NaCl, 0.1% $CaCl_2$), we measured mobilities of a nitrogen foam in cores with permeabilities from 7.5 to 900 md

(750 psi back pressure, 41°C) with foam qualities ranging from 50% to 95% and with injection rates (Darcy velocities) ranging from 0.5 to 100 ft/d. Figs. 2 and 3 illustrate some of these results. We also extensively studied the residual resistance factors provided during brine injection after foam placement. We confirmed the predictions of Khatib et al. that (1) no foam is formed in low-permeability rock (7.5 md in our case), (2) foam mobility decreases with increased permeability in rock with intermediate permeabilites (10 to 80 md), and (3) foam mobility increases with increased permeability in rock with high permeabilites (above 500 md). Using our experimental results and numerical analyses, we found that the foam could provide superior placement and permeability-reduction properties (compared with gelants) if the offending thief zones have permeabilities of 80 md or greater and the oil zones have permeabilities less than 10 md. The foam will not be superior to gelants if all zones have permeabilities that are 80 md or greater.

References

1. Khatib, Z.I., Hirasaki, G.J., and Falls, A.H.: "Effects of Capillary Pressure on Coalescence and Phase Mobilities in Foams Flowing Through Porous Media," *SPERE* (Aug. 1988) 919-926.
2. Radke, C.J. *et al.*: *Colloids and Surfaces A* (1994) **83**, 109.

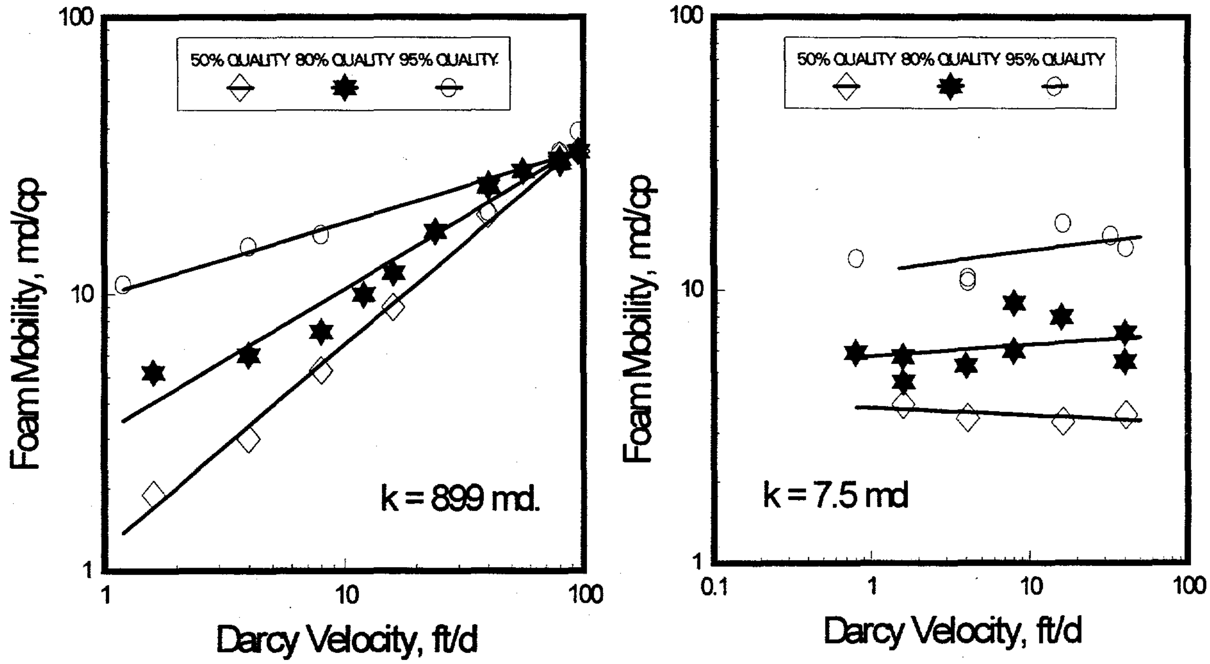

Fig. 2. Foam Mobility Versus Fluid Velocity and Foam Quality.

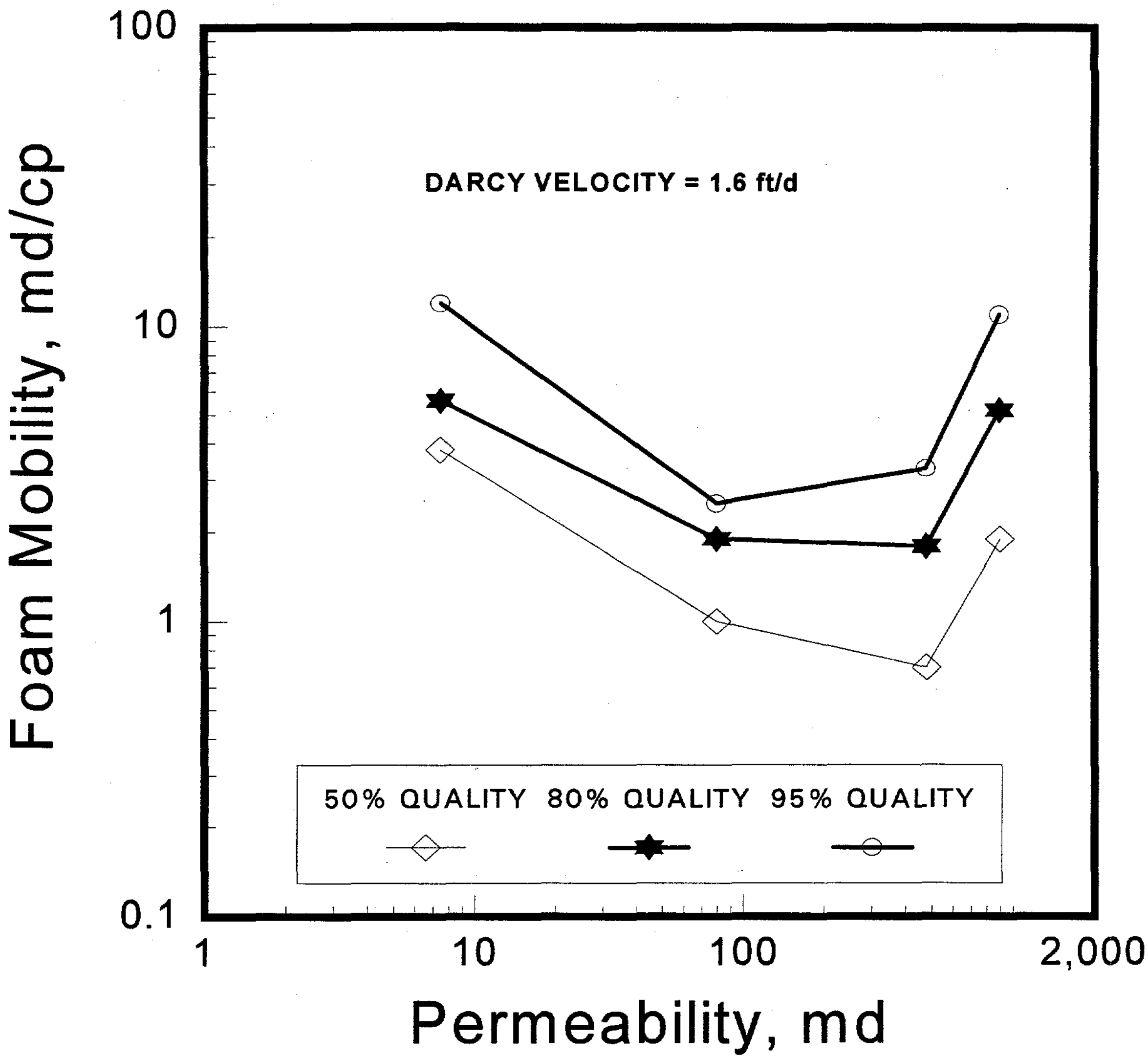

Fig. 3. Foam Mobility Versus Permeability.