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Simulation of the Bishop Steam Foam Pilot

by T.W. Patzek and N.A. Myhill, Shell Development Co.

SPE Members

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ABSTRACT

In this paper we present a simple model of steam foam transport and apply it to the Shell Kern River Bishop pilot. The only adjustable parameter in the model is an effective surfactant partition coefficient that accounts for surfactant losses and inefficiencies of foam generation, and determines foam propagation rate. Once this partition coefficient is calibrated to match observed foam growth in the pilots, the simulator correctly predicts an incremental 5.5 percent OOIP recovery due to steam foam and additional 3 percent OOIP due to infill wells.

"What-if" simulations using an "enhanced" steam foam (twice as strong as AOS-1618, propagates 20 percent faster and reduces ROS by 7 percent) show a dramatic increase in incremental oil recovery (17 versus 5.5 percent OOIP in the Bishop pilot) and a dramatic reduction in surfactant requirement (5 versus 15 lbs AOS/Bbl incremental oil).

SUMMARY OF PILOT RESULTS

As discussed in Reference 1, Shell has conducted two steam foam pilots in the Kern River Field (Figure 1), one on the Mecca Lease (1980-1985) and the other on the Bishop Fee (1982-1986). Both pilots consisted of four contiguous inverted five-spots covering 12 and 14 acres (0.05 and 0.06 km^2), respectively. The Mecca pilot was started after 9 years of steam soaks and 10 years of unconfined steam drive, whereas Bishop was preceded by 19 years of steam soaks and 1 year of drive. Steam foam in both pilots was generated by continuous injection of 250 B CWE/D/pattern (39.7 m^3/d), 50 percent quality steam with 4 wt percent NaCl and 0.5 wt percent AOS-1618 in the aqueous phase and 0.06 mole percent N_2 in the vapor. Each pilot w thoroughly monitored with the use of 8 logging observation wells.

Following is a summary of pilot results[1] as one moves from the injecti towards the producer:

- Mobility reduction factors in the field agreed well with laborato measurements at similar flow conditions (Figure 2).
- Foam conveyed some steam along the reservoir bottom, th improving vertical sweep.
- Foam zone growth was roughly constant and the same in bo pilots; 1 PV of the foam was generated by 2/3 PV of injecte surfactant solution (Figure 3).
- Major oil production response in Bishop (and in Mecca) occurre after 2 years of foam injection (Figure 4).
- In the confined Bishop pilot, incremental oil due to foam was least 5.5 percent OOIP (Figure 5); surfactant required was most 15 pounds per barrel.
- Infill wells at Bishop caused more than the above amount of oil be captured - 8.5 percent OOIP after 5 years (Figure 5).
- The unconfined Mecca pilot may be impossible to interpr quantitatively.

FOAM MODEL

Simulations of the Bishop pilot have been performed with a simp steam foam model that assumes the following:

- Steam foam is steam with a lower mobility.

References and illustrations at end of paper.

- Foam exists whenever both aqueous surfactant and steam are present in a grid block.
- Surfactant is lost from water by partitioning into oil.
- Propagation of aqueous surfactant is governed by a single constant effective partition coefficient (Figure 6) that accounts for surfactant precipitation, adsorption, and true partitioning,[2] as well as inefficiencies of foam generation.[3-5]
- The numerical value of the effective partition coefficient is adjusted so that the simulated propagation rate of surfactant equals the actual growth rate of foam in the Kern River pilots (Figure 3).
- Foam mobility is equal to gas relative permeability divided by steam viscosity and a mobility reduction factor.
- The mobility reduction factor is an increasing function of surfactant concentration in water and is based on laboratory data (Figure 8).

The foam model described above was implemented in a predecessor of Scientific Software Intercomp's THERM simulator.[8]

Our simple foam model involves an enormous amount of "lumping" and is in no way capable of describing all potential consequences of foam injection. At the same time, it does appear to capture the first order effects as observed in the Shell Kern River pilots.

The effective partition coefficient was the only parameter adjusted in the simulations to make a zone of 0.1 wt percent surfactant concentration grow at the same rate as the foam in the pilots (Figure 7); the simulated foam front at this particular surfactant concentration increased the reservoir temperature by the 10°F, detectectable in the pilot observation wells at foam breakthrough. The resulting effective partition coefficient in the pilot simulations was noticeably higher (Figure 9) than that backed-out from surfactant propagation experiments[2] in Kern River cores at S_{orw} (no foam present) and the average temperature of foam-swept zones in the pilots.

Two possible reasons why growth of AOS-1618 foam in the field was slower than propagation of the aqueous AOS-1618 in the laboratory are:

- Surfactant propagation in the field was simply slower than in the corefloods.
- Foam propagation in the field lagged surfactant propagation in the field.

Surfactant propagation in the field could have been slower than in the corefloods because:

- Calcium concentration decreased at a slower rate (more crossflow and dispersion).
- Surfactant was exposed to more oil (more partitioning).
- Temperature at the reservoir bottom was lower (more adsorption) than in the corefloods.

There is no direct evidence that foam propagation in the pilots was slower than surfactant propagation; however, foam growth commonly lags surfactant transport in laboratory experiments,[5] even without oil.

A foam broken by contact[7] with oil does not propagate until after the oil has been displaced. If this is the case, then any surfactant that emulsifies oil into droplets smaller than the pore necks should be superior[8] because it will remove the oil and form a foam that may propagate almost as fast as the surfactant itself.

SIMULATION MODEL

A prototype Bishop steam foam pilot pattern was simulated as follows:

- 7x4x5 3-D element-of-symmetry of a 3.5-acre "almost 5-spot" (injector:producer ratio = 1:1.25).
- 100-ft thick, homogeneous, 2-darcy sand; k_v:k_h = 1:4, net:gross = 0.8, S_{oi} = 0.7.
- Relative oil-water and oil-gas relative permeability curves as in Figure 10 ($S_{wc} = S_{wr} = 0.3$, $S_{orw} = 0.25$, $S_{org} = 0.1$, and $S_{gr} = S_{gc} = 0.05$) and linear three-phase oil isoperms.
- 13° API oil, with an initial viscosity of 2200 cp at 100°F, and solution GOR = 70 SCF/B.
- Cumulative recovery was 27 percent OOIP after primary (8 percent OOIP) and steam soaks (19 percent OOIP).

The effect of 2 infill and 2 replacement wells in the Bishop pilot (diamonds in Figure 1) was simulated in the following manner:

- An equivalent infill/replacement producer that increased the injector:producer ratio to 1:2 was added after 2 years of foam injection (cases labeled "all wells").
- The initial injector:producer ratio of 1:1.25 was increased to 1:1.5 after two years of foam injection (cases labeled "w/o infill").

Vents were assumed to be closed and steam injection was based on field data (Figure 11).

A prototype Bishop Fee pattern was modeled similarly, but with an injector:producer ratio of 1:1 and a steam injection rate given by the broken curve in Figure 11.

SIMULATION RESULTS

With the above model, the Fee was matched and the major oil response in the Bishop pilot predicted both with and without the infill wells (Figures 12 and 13). It is important to understand that apart from adjusting the partition coefficient to match the foam growth in the pilots, all other input parameters described the Bishop pilot to the best of our knowledge. That is, the simulator predicted the oil actually captured and further validated our interpretation of the pilots.

As in the field,[1] the simulated steam foam emanated spherically from the injector (Figure 14, bottom) until the flow pattern was altered by the reservoir boundaries. The foam retarded severe gravity overlay of steam (Figure 14, top) and improved vertical sweep. However, it was the steam, whistling through the foam, that actually displaced the additional oil.

IMPROVED PERFORMANCE

"What-if" simulations were also run and indicated that an increase in the surfactant injection rate at constant heat injection should significantly accelerate (Figure 15) production, but with only a slight increase in the ultimate recovery (Figure 16).

However, if an "enhanced" foam that is twice as strong as AOS-1618, propagates 20 percent faster, and reduces ROS by 7 PV percent were to be used, the incremental recovery at Bishop should increase to 17 percent OOIP and surfactant requirement decrease to 5 lbs/incremental barrel of oil (Figure 16). Such a foam may be available[8] for reservoirs cleaner than the Bishop "Q" Sand, but has yet to be tested in the field.

CONCLUSIONS

Our analysis of Shell's Kern River steam foam pilots now includes successful simulations of the confined Bishop pilot and the Bishop Fee. The only adjustable parameter in the simulations is an effective surfactant partition coefficient that determines the foam propagation rate. Once this parameter is fixed, the simulator correctly predicts an incremental 5.5 percent OOIP due to steam foam and additional 3 percent OOIP due to infill wells.

On paper, an "enhanced" foam dramatically increases incremental oil recovery (17 versus 5.5 percent OOIP in the Bishop pilot) and dramatically reduces the surfactant requirement (5 versus 15 lbs AOS/Bbl incremental oil).

ACKNOWLEDGEMENTS

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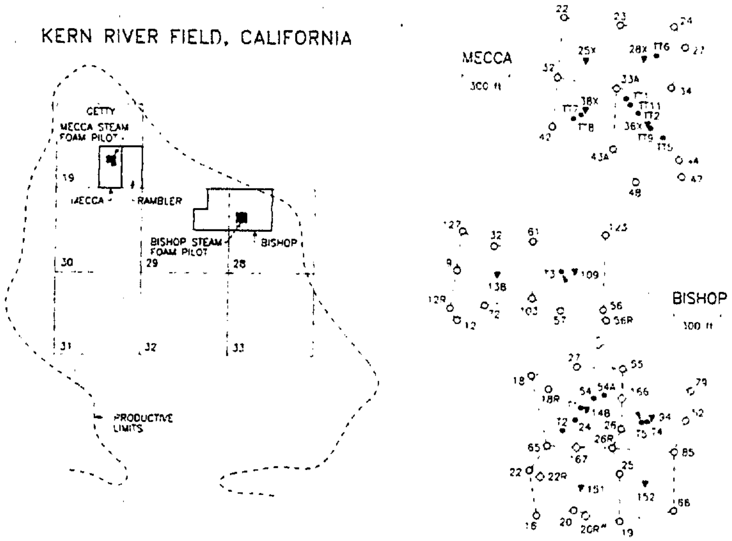

Fig. 1—Kern River steam foam pilots.

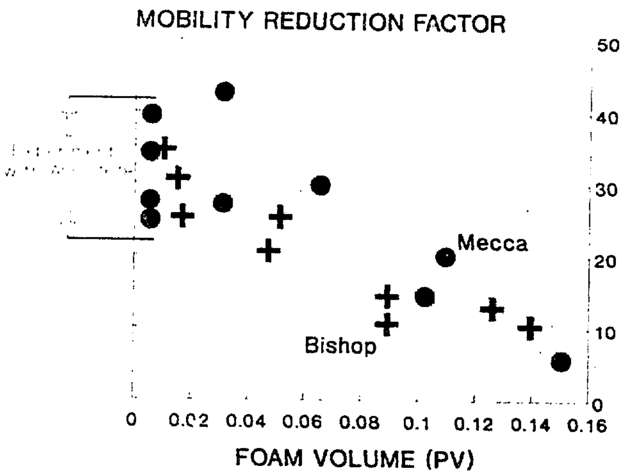

Fig. 2—A snapshot in time of the mobility reduction factors (Ref. 1) for AOS-1618 foams vs. PV. The cumulative PV of surfactant solution was 0.2 in Bishop and 0.3 in Mecca.

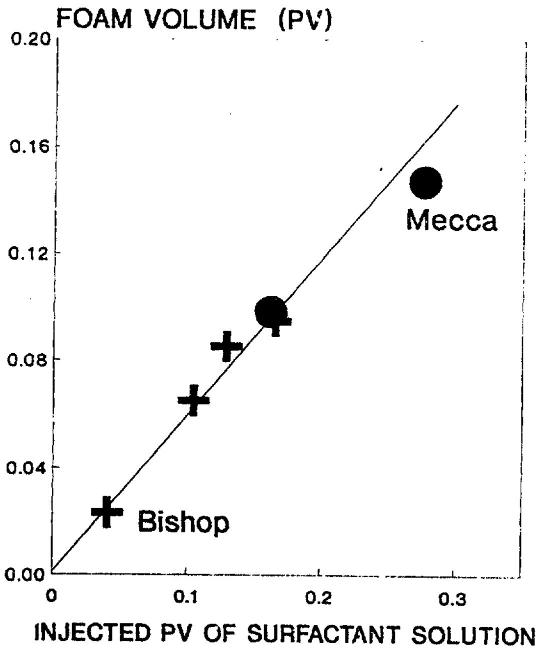

Fig. 3—Volumetric approach of steam foam zones in the Kern River pilots (Ref. 1).

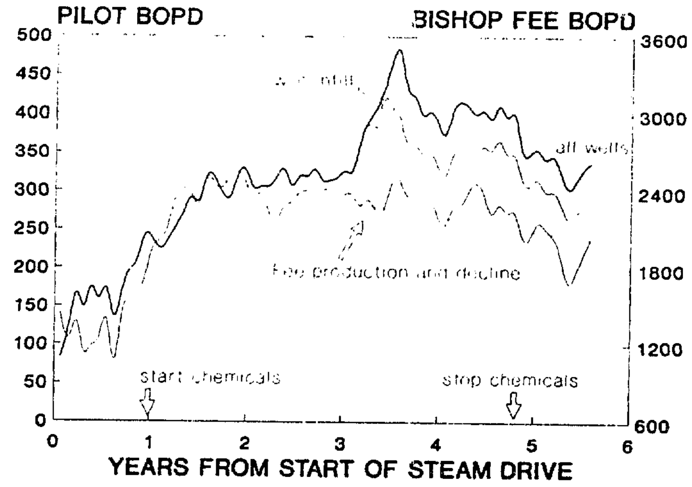

Fig. 4—History of the pilot oil production with and without infill wells; the Bishop Fee production decline shown for comparison.

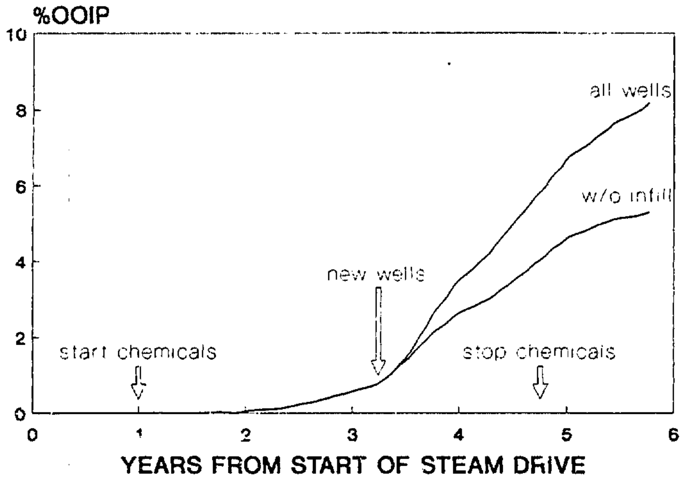

Fig. 5—Incremental oil production in the Bishop pilot with and without infill wells.

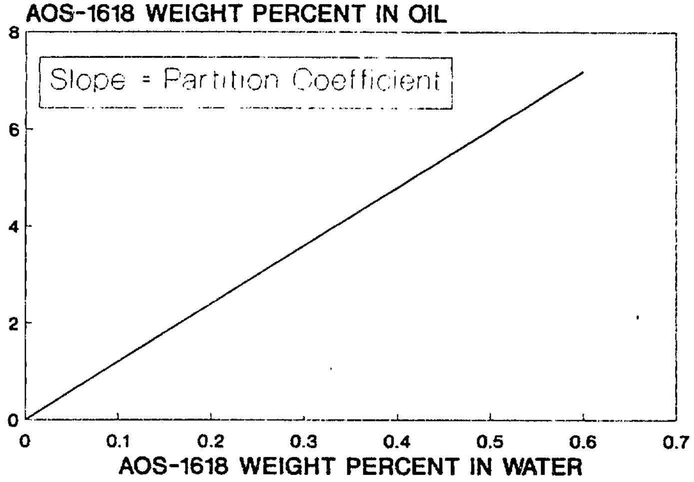

Fig. 6—Constant effective partitioning of AOS-1618 into the oleic phase.

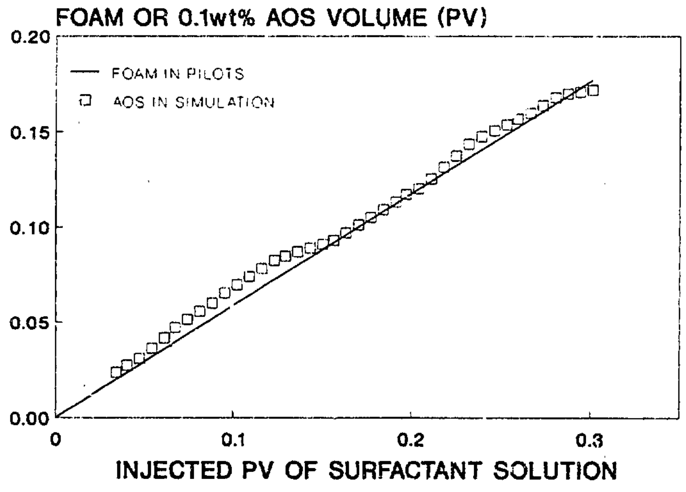

Fig. 7—Match of foam growth in the pilots (cf. Fig. 3).

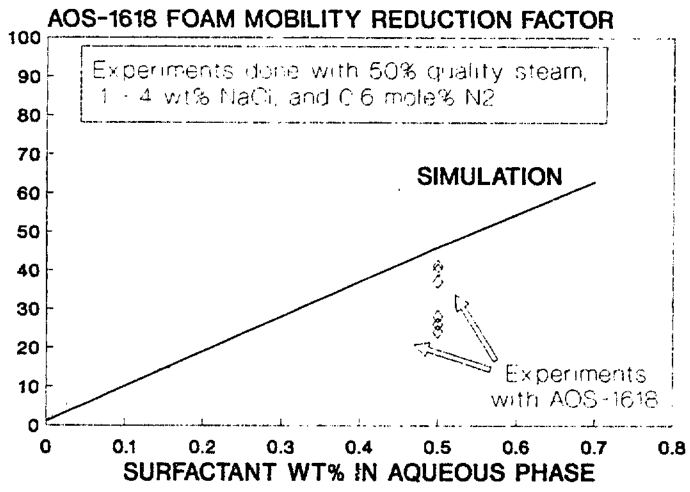

Fig. 8—Comparison of the mobility reduction factor in the simulations with laboratory experiments.

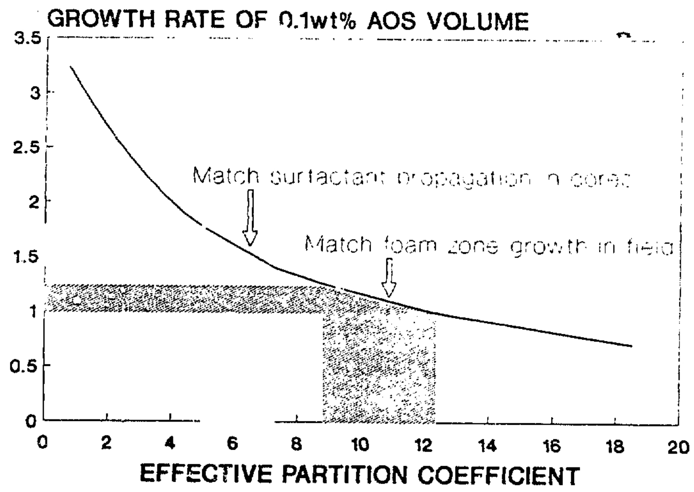

Fig. 9—Effective AOS partition coefficient in the simulations is 50% higher than that calculated from corefloods.

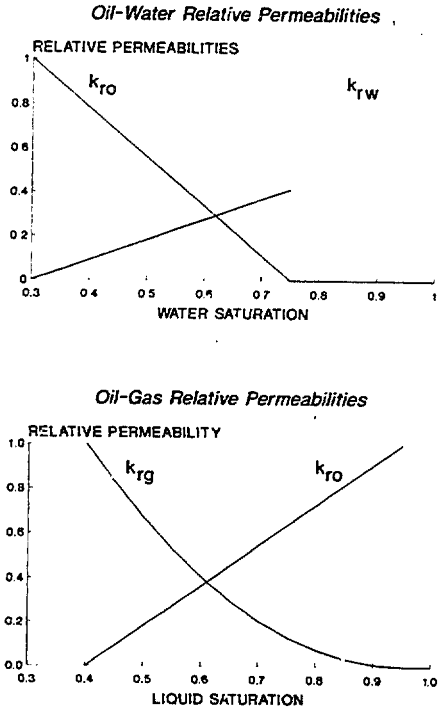

Fig. 10—Relative permeability functions.

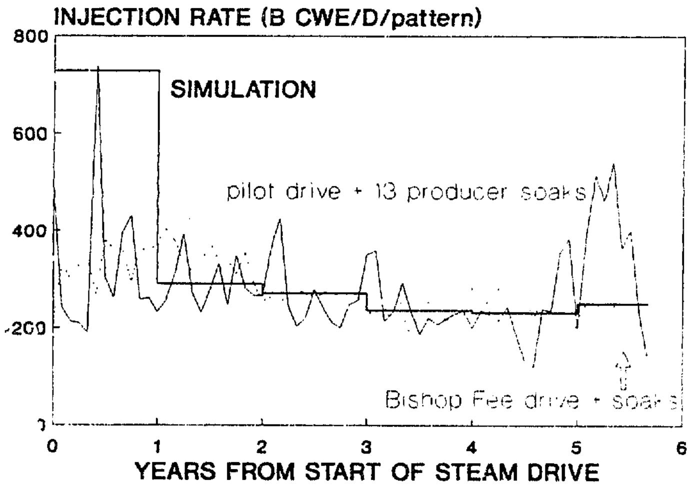

Fig. 11—History of steam injection in the Bishop Pilot and Fee, and injection schedule in the pilot simulations.

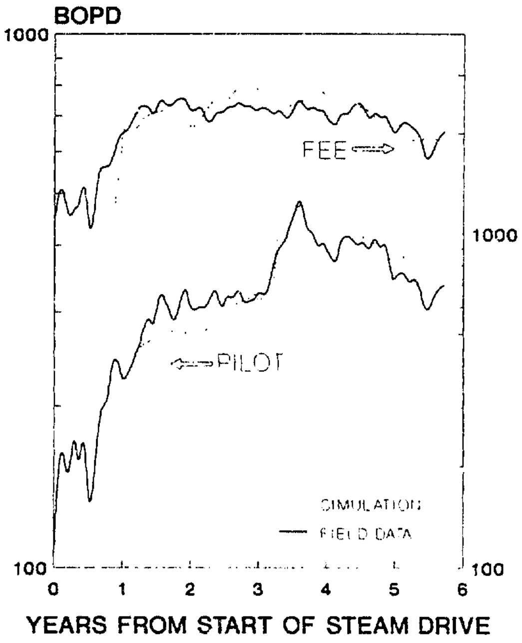

Fig. 12—Match of the Bishop Fee and Pilot oil rates.

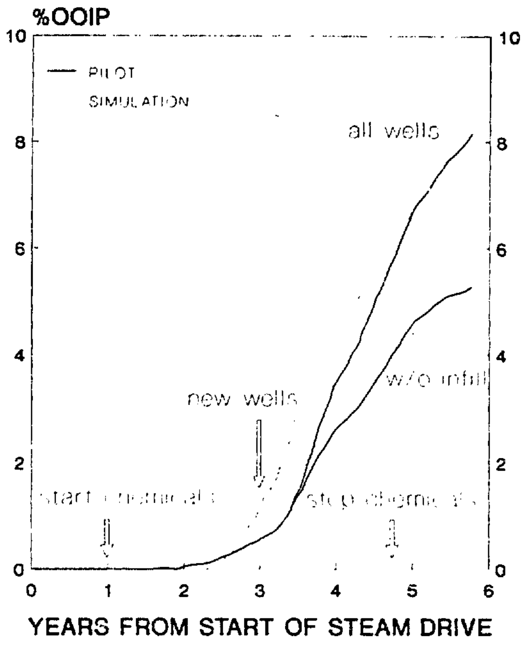

Fig. 13—Match of the pilot incremental production with and without the infill wells.

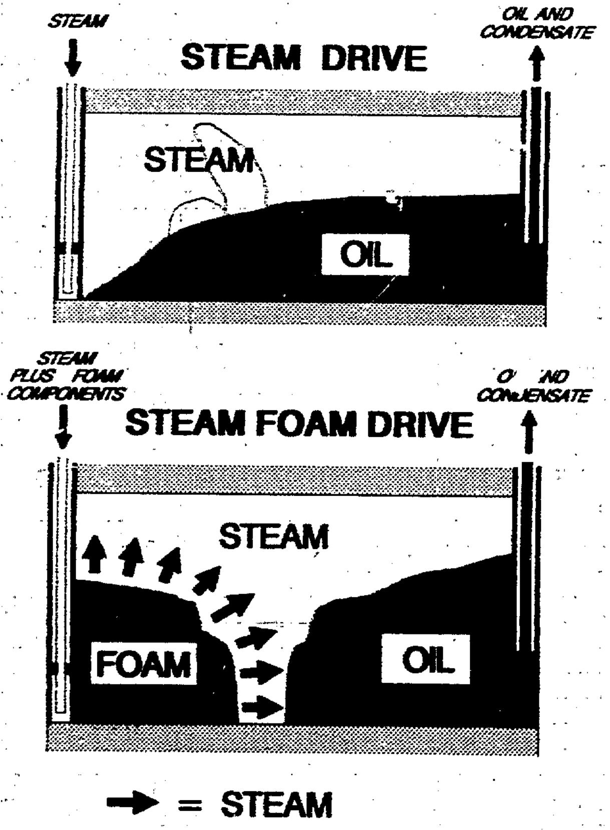

Fig. 14—Comparison of a mature steam and new steam foam drive in Kern River.

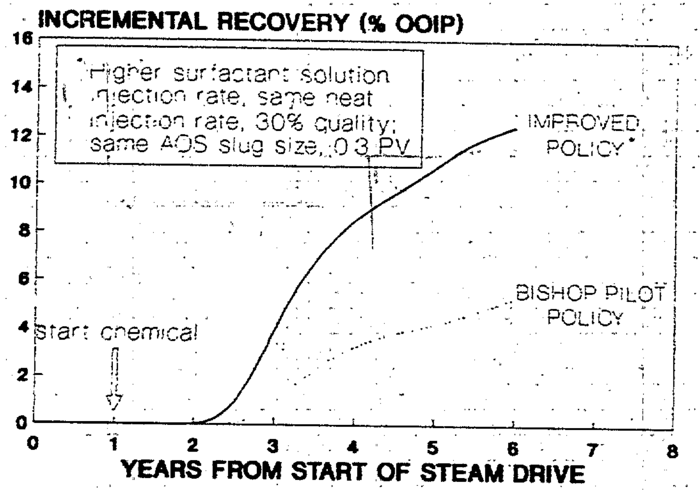

Fig. 15—Effect of an improved steam foam injection policy on the pilot oil response.

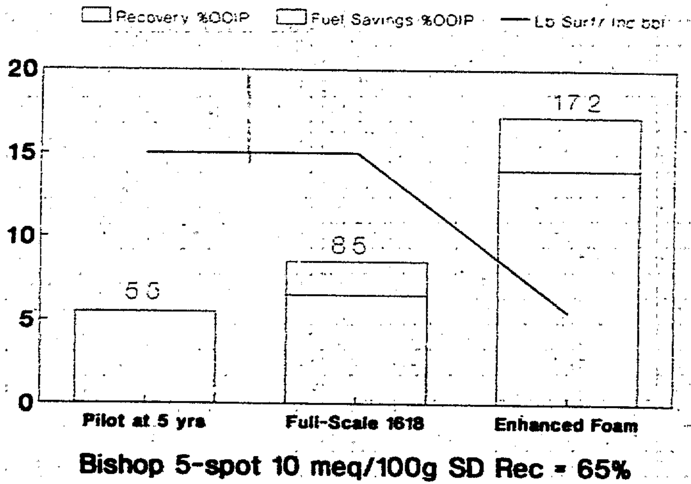

Fig. 16—Incremental recovery and pounds AOS/barrel of incremental oil for three steam foam designs.