Kern River Steam-Foam Pilots

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Summary. Shell conducted two steam-foam pilots in the Kern River field, one on the Mecca lease (1980–85) and the other on the Bishop fee (1982–86). The pilots consisted of four contiguous inverted five-spots covering 12 and 14 acres [4.8 and 5.7 ha], respectively. The Mecca pilot began after 9 years of steam soaks and 10 years of unconfined steamdrive; the Bishop pilot was preceded by 19 years of steam soaks and 1 year of steamdrive. Steam foam in both pilots was generated by continuous injection of 250 B/D [39.7 m³/d] per pattern [cold water equivalent (CWE)] of 50% quality steam, with 4 wt% NaCl and 0.5 wt% AOS-1618 surfactant in the aqueous phase and 0.06 mol% N_2 in the vapor.

Introduction

The Kern River oil field is in the eastern San Joaquin Valley about 4 miles [6.4 km] north of Bakersfield, CA. The productive sand intervals (Sands J, M, and Q) were deposited in the Pliocene and Pleistocene as a high-energy alluvial-channel complex. Both pilots (**Fig. 1**) are near the northeast and eastern (updip) boundaries of the Kern River field (**Fig. 2**). Compared to the heart of the field, the pilot areas are characterized by a higher content of pore-filling clays, lower oil gravity and higher viscosity, and lower net/gross pay ratios. **Tables 1 and 2** give concise, chronological pilot summaries.

Geology

The steamdriven Sand M in the Mecca pilot (**Fig. 3 and Table 3**) is divided into the Upper, Main, and Poor M sands. The Upper M is about 15 ft [4.6 m] thick and is separated from the Main M by a 3- to 5-ft [0.91- to 1.52-m] clay or clayey-silt layer that is seemingly continuous across the pilot area, with the exception of the northeastern producer, Mecca Well 27. Below this clay break, there is a 40-ft [12.2-m] -thick sand package, the Main M, which has no significant silt or clay breaks.

The Poor M comprises the remaining 25 ft [7.62 m] between the Main M and the Sand M base. No definite breaks separate the Poor M from the Main M. In some wells, the Poor M grades from a good-quality sand to a poor-quality pebbly sand mixed with silt and clay. In other wells, the Poor M consists of pebbly sand, silts, and clays randomly mixed throughout the interval. These silt and clay layers do not appear to be continuous from well to well. Average gross thickness for Sand M in the Mecca pilot is 83 ft [25.3 m], and net pay thickness is 67 ft [20.4 m]. The remaining 16 ft [4.9 m] can be split between poor sand (7 ft [2.1 m]) and clay or clayey silts (9 ft [2.7 m]). The geometrical pilot area is 11.6 acres [4.7 ha]. Because steam foam invaded the Poor M, the net pay thickness was adjusted to 74 ft [22.6 m], increasing the original oil in place (OOIP) in the geometrical pilot area from 1,190,000 to 1,400,000 STB [189×10^3 to 223×10^3 stock-tank m³]. The latter value is the upper bound on the volume of oil originally in the Mecca pilot.

Sand Q in the Bishop pilot (**Fig. 4**) is a 100-ft [30.48-m] -thick sand package divided into several layers by 0 to 3 clay or clayey-silt barriers that are continuous across at least a single pilot pattern and by 0 to 3 discontinuous barriers that are randomly distributed throughout the pilot area. Average pay thickness of good sands in the Bishop pilot is 65 ft [19.8 m] and total thickness of barriers is 15 ft [4.6 m], and there is 20 ft [6.1 m] of poor-quality sand. The OOIP in the geometrical pilot area (14 acres [5.7 ha]) is 1,500,000 STB [238×10^3 stock-tank m³].

Cation exchange capacity (CEC) is 8 meq/100 g in Mecca Sand M and approaches 9 meq/100 g in Bishop Sand Q. These large CEC's are caused by a high content of montmorillonite and illite (85% in calcium and magnesium form initially).

Oil in the Tank

The Kern River pilots were designed to evaluate the performance of steam foam when applied either very late in a steamdrive (10 years at Mecca) or very early (1 year at Bishop). Production and injection histories of the pilots are detailed in **Table 4.**

In evaluating the pilot performance, we are interested only in the *incremental* oil production resulting from improved volumetric sweep by steam foam (observed in both pilots), and possibly from reduction of residual oil saturation (ROS) in the foam-swept zones (none with AOS-1618). We are disregarding any *acceleration* of oil production, such as the early response of the Mecca pilot immediately after the start of foam injection.[1]

An unconfined steamdrive was run during 1970–80 at Mecca. Such a drive in a dipping reservoir should produce more oil than a corresponding confined drive, and possibly even more than the OOIP because of gravity drainage. Because drainage from updip easily could have amounted to some 30% of OOIP in the Mecca pilot, the average oil saturation at the beginning of the foam drive is believed to have been higher at Mecca

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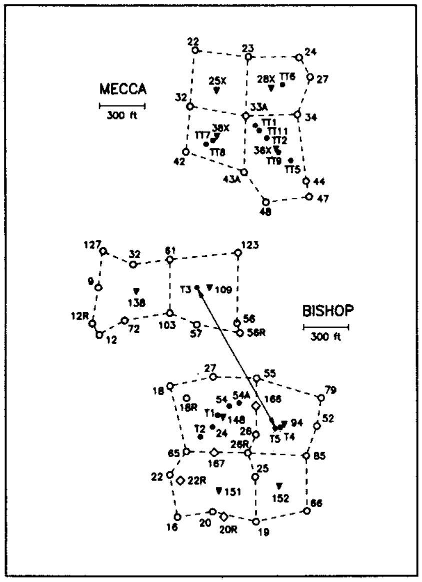

Fig. 1—Kern River steam-foam pilots.

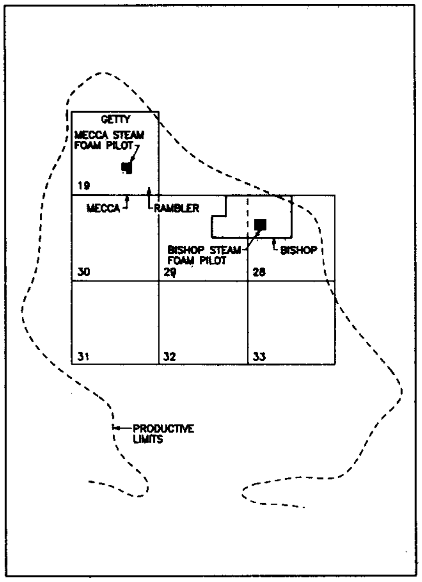

Fig. 2—Kern River oil field, California.

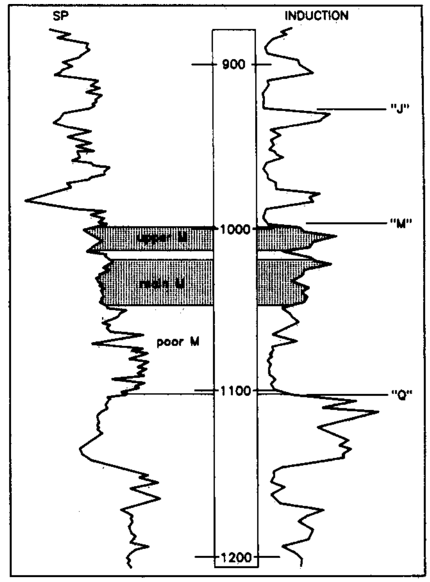

Fig. 3—Mecca type log.

TABLE 1—CHRONOLOGY OF EVENTS AT MECCA STEAM-FOAM PILOT

April 1970	Drilled Wells TT2 and TT1, 90 and 185 ft northwest of Well 36X; neither was perforated
May 1970	Began steamdrive pilot; average steam-injection rate 250 B/D CWE per injector, 50% quality; all injectors completed across bottom 16 to 18 ft of Main M
Oct. 1976	Drilled Well TT5, 110 ft southeast of Well 36X; perforated at 1,034 to 1,050 ft to draw liquid samples and measure pressure
	Began 5-month steam-foam-injection test in Well 36X (see Dilgren *et al.*[2])
Aug. 1979	Drilled Well TT6, 75 ft northeast of Well 28X
July 1980	Began steam-foam pilot with 0.5 wt% Siponate® DS-10, 4 wt% brine, 250 B/D CWE per injector, 50% quality steam
Nov. 1980	Getty completed installation of steamdrives north, west, and south of Mecca lease
Dec. 1980	Changed surfactant to Neodene® 1618, 4% brine
Aug. 1981	Changed brine to 1%
Oct. 1981	Closed vents in pilot producers
Feb. 1982	Opened vents in pilot producers
March 1982	Changed surfactant to Siponate A-168, 4% brine
June 1982	Major oil-production response began
Sept. 1983	Drilled and cored dual-completion Observation Well TT9, 20 ft southwest of Well 36X, one tube perforated at 1,033 to 1,044 ft to measure pressure; oil saturation averaged over entire Upper and Main M was 9.2%
	Drilled and cored dual-completion Observation Well TT8, 70 ft southwest of Well 38X, perforated at 1,077 to 1,072 ft; oil saturation averaged over entire Upper and Main M was 16.7%
Dec. 1983	Doubled steam-injection rate in Wells 36X and 38X to 500 B/D; shut in Wells 25X and 28X
March 1984	Closed vents in selected pilot producers
April 1984	Returned to 250 B/D CWE in all four injectors
July 1984	Returned to double injection rate in Wells 36X and 38X, shut in Wells 25X and 28X
Aug. 1984	Drilled Well TT11, 140 ft northwest of Well 36X, just outside predicted foam front; not perforated
Nov. 1984	Squeezed or isolated perforations in Wells TT5 through TT9 to avoid interference from steam flow
Jan. 1985	Arrival of steam-foam front detected in Well TT11
Feb. 1985	Shut in steam and chemicals in the pilot; incremental oil recovery was 12% OOIP

TABLE 2—CHRONOLOGY OF EVENTS AT BISHOP STEAM-FOAM PILOT

Aug. 1981	Began steamdrive on Bishop fee
Jan. 1982	Drilled Well T1, 45 ft west of Well 148X as a pressure and sampling observation well
June 1982	Began collecting liquid samples in Well T1
Aug. 1982	Began injection of 0.5 wt% Enordet® AOS-1618, 4% brine, 260 B/D CWE per injector, 50% quality steam. Three injectors completed over bottom 25 ft of Sand Q, Well 94X completed full-interval
Nov. 1982	Stopped collecting liquid samples in Well T1; well steamed out
Dec. 1982	Drilled Well T2, 180 ft southwest of Well 148X as a pressure and temperature observation well
	Began monitoring steamdrive comparison pattern in Well 109X, 800 ft northwest from the pilot, drilled Well T3, 70 ft west of Well 109X; perforated at 668 to 673 ft
Jan. 1983	Converted Well T1 to a pressure and temperature observation well
Feb. 1983	Converted Bishop Well 24 to a temperature observation well
	Converted Bishop Well 54 to a temperature observation well
	Converted Bishop Well 54A to a pressure observation well
Nov. 1983	Bishop Well 54 showed gas saturation below shale
Jan. 1984	Bishop Well 54 showed dramatic temperature increase below shale; arrival of steam-foam front detected
April 1984	Drilled and cored Well T4, 20 ft southwest of Well 94X, a full-interval injector; Well T4 showed evidence of foam over entire Sand Q, oil saturation averaged across entire Sand Q was 10.5%
	Drilled and cored Well T5, 70 ft southwest of Well 94X; Well T5 showed brine over most of Sand Q and gas saturation (without salt) at the top of Sand Q; oil saturation averaged over entire Sand Q was 20%
Oct. 1984	40% increase in oil rate to over 500 BOPD
Dec. 1984	Squeezed or isolated perforations in Bishop Wells T1 and T2
	Began drilling two replacement and two infill producers
Feb. 1985	Replacement producers Bishop Wells 20R and 22R and infill producers Bishop Wells 166 and 167 became operational
April 1986	Stopped chemicals; incremental oil recovery was 7% OOIP

TABLE 3—RESERVOIR DESCRIPTION OF MECCA AND BISHOP PILOTS

	Mecca Sand M	Bishop Sand Q
Depth, ft	~1,000	~600
Dip, directional degrees	3 southwest	3 southwest
Gross thickness, ft	83	99
Good sands, ft	67	65
Poor sands, ft	7	19
Silt or clay, ft	9	15
Net pay, ft	67+7=74	65
S_{oi}, %	70	70
Porosity, %	30	30
Four-pattern area, acres	11.6	14.0
PV, thousand bbl	2,000	2,200
OOIP, thousand STB	1,400	1,500
API gravity, degrees	13	13
Barriers:		
Continuous within a pattern	1	0 to 3 random
Discontinuous within a pattern	random in lower one-third of Sand M	0 to 3 random
CEC, meq/100 g	8	9

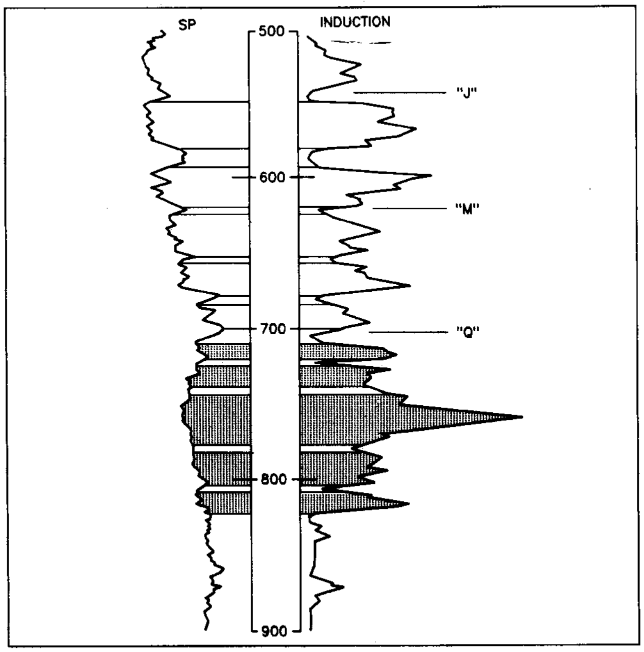

Fig. 4—Bishop type log.

TABLE 4—INJECTION AND PRODUCTION HISTORIES FOR MECCA AND BISHOP PILOTS

Item	Mecca	Bishop
Primary oil produced		
Thousand bbl	95	120
% OOIP	6.8	8.0
Steam Soaks (Production Allocated)		
Years	9	19
Steam injected		
Thousand bbl CWE	475	568
PV CWE	0.24	0.26
Oil produced		
Thousand bbl	210	286
% OOIP	15.0	19
Gross production/injection	1.5	1.2
Cumulative OSR	0.44	0.50
Steamdrive (Production Allocated)		
Years	10	1
Steam injected		
Thousand bbl CWE	4,212	424
PV CWE	2.11	0.18
Oil produced		
Thousand bbl	402	30
% OOIP	28.7	1.9
Gross production/injection	0.4	0.3
Cumulative OSR	0.10	not applicable
Total Oil Recovery Before Foam Injection		
Thousand bbl	707	316
% OOIP	50	29
Foam Drive (Production Not Allocated)		
Years	4.5	3.7
Foam injected		
Thousand bbl CWE	1,590	1,416
PV CWE	0.80	0.65
Oil produced		
Thousand bbl	345	486
% OOIP	24.6	32.0
Surfactant injected, thousand bbl (100% active)	1,390	1,240
Incremental oil after 5 years from start of foam		
Thousand bbl	196	127/82*
% OOIP	14	8.5/5.5*
lbm surfactant/bbl incremental oil	7.1	9.8/15.1*
Gross production/injection	1.55	1.42
Delay of major oil response, years	2	2
Injected foam volume at major response		
Thousand bbl CWE	730	800
PV CWE	0.37	0.36

*With/without infill.
OSR = oil/steam ratio.

than at Bishop. Moreover, the aggressive steam drives by Getty Oil Co. (600 B/D [95.4 m^3/d] CWE per injector), begun on three sides of the Mecca lease concurrently with steam-foam injection, probably created a pressure barrier that kept fluids from leaving the pilot and allowed the pilot producers to capture additional oil from the surrounding oil-rich area. Dalton *et al.*[2] documented this phenomenon for waterflood pilots.

The incremental oil resulting from steam-foam injection in Mecca is calculated as the difference between the well-established decline of oil production in the previous steamdrive and the actual oil production from the pilot wells.

The Bishop pilot was confined. Before the steamdrive (1981), the entire fee was extensively steam-soaked for more than 19 years; and there is no evidence that oil drained into the pilot area. To improve the injection/production balance, four infill/replacement wells were drilled while the foam pilot was in progress. Production improved, but the major oil response occurred before the new producers became operational.

The incremental oil resulting from steam-foam injection in Bishop is calculated as the difference between the average decline of oil production in 43 steamdrive patterns on the Bishop fee and the actual oil production from the pilot wells.

Of the two pilots, the confined Bishop is much easier to evaluate in oil-in-the-tank terms than the unconfined Mecca. In the Bishop pilot, a definite oil-production response occurred after 2 years of foam injection or after 3 years of steam injection (**Fig. 5**); there was no such response anywhere else on the fee. Evaluation of the Bishop pilot was complicated by the steam soaks performed on old producers to link them to the injectors and by the drilling of the two replacement and two infill wells. As **Figs. 6 and 7** show, the new wells dominated the response, but 13 of 20 wells contributed (9 of 16 old producers). An old unsoaked well (Bishop Well 27) produced the second-largest response. On the basis of the production decline of all steamdrive patterns at the Bishop fee, the cumulative incremental oil recovery was 8.5% OOIP after 3.7 years of foam injection, followed by 1 year of steam injection and about 5.5% OOIP without infill wells (Fig. 6). Subsurface data obtained during the pilot show that unique oil was displaced by steam foam from the lower portion of the pay. The capture of this oil resulted in the increased production rate.

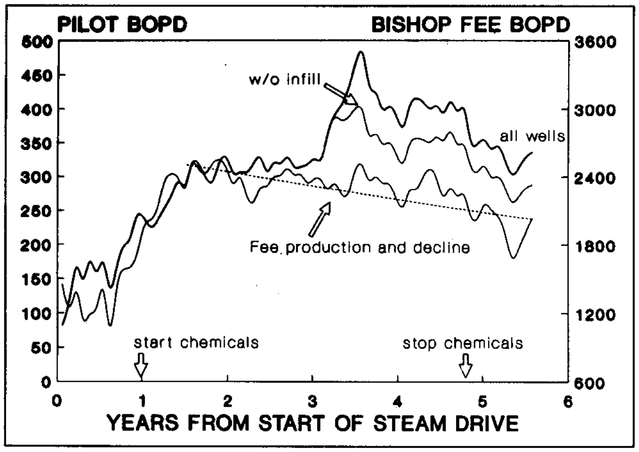

Fig. 5—Incremental production in Bishop steam-foam pilot.

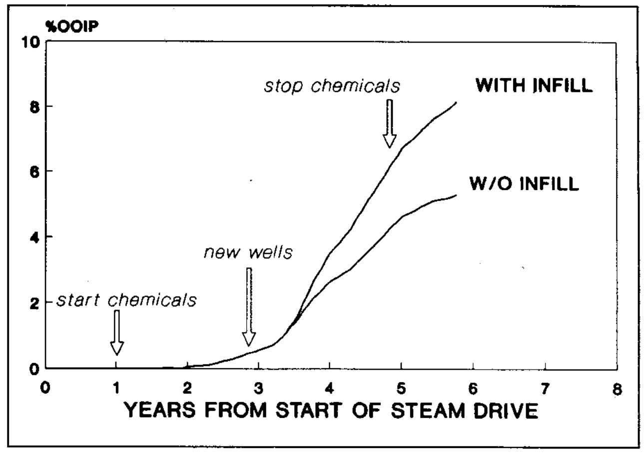

Fig. 6—Cumulative incremental oil recovery in Bishop pilot.

In the Mecca pilot, unallocated oil production exceeded the OOIP and some of the produced oil drained from updip. A major oil-production response occurred after 2 years of foam injection or after 12 years of steam injection (**Fig. 8**). Part of the production response was a result of the pilot's lack of confinement, which was amplified by steamdrives around the Mecca lease. On the basis of the steamdrive production decline, incremental oil recovery was 14% OOIP 5 years after the start of foam injection (**Fig. 9**). All injection ceased in Feb. 1985, but an additional 4% OOIP was produced during the next 2 years.

Performance of the Mecca pilot has always been difficult to interpret, and the continued production after shut-in is difficult to analyze because of interference from the surrounding Getty drive and an adjacent steamdrive on the Rambler lease. We believe, however, that a significant factor sustaining the Mecca pilot's production was a slow release of energy stored in the foam zone. A simplified analysis of the transient response to the foam-injection shut-in indicates that it may take many months for the reservoir pressure to decline if the foam does not collapse immediately. This phenomenon occurs because the sensible heat stored in the rock gradually vaporizes water in the reservoir, causing the steam zone to expand and additional oil to be produced. These calculations are supported by the slow decline of temperatures and downhole pressures in the Mecca observation and injection wells.

Summary of Subsurface Results

Temperature surveys were run once a month and neutron logs were run every 3 months in each pilot's eight observation wells (see Tables 1 and 2). Some wells were also perforated or dual-completed to serve as pressure observers (Mecca Wells TT5 through TT9, and Bishop Wells T1 through T3 and 54A). All perforations in the observation wells were squeezed or isolated in Nov. 1984 to eliminate the negative impact of steam flow in the wellbore on the resolution of temperature and neutron logs. Mecca Well TT5 and Bishop Well T1 served as liquid sampling wells. Downhole injection pressures were measured continuously in all four Mecca injectors between Nov. 1983 and June 1985.

Improved Vertical Sweep. Changes in vertical sweep resulting from steam foam were indicated by temperature surveys and gamma-ray-neutron (GRN) logs simultaneously run in the pilot observation wells. When an increase in gas saturation (above

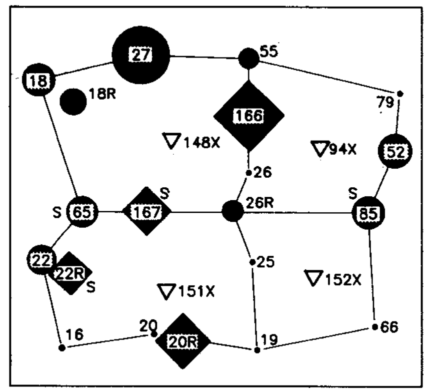

Fig. 7—Average oil rates in Bishop pilot wells. Diamond shapes represent new wells, an S indicates soak near the time of overall foam response, and the size of circles or diamonds is a qualitative response indicator.

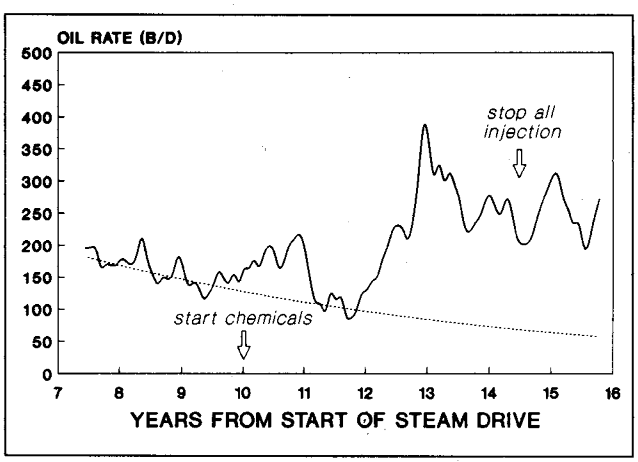

Fig. 8—Incremental production in Mecca steam-foam pilot.

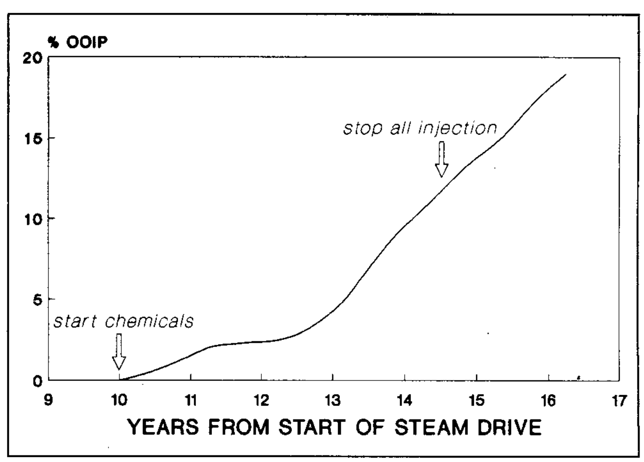

Fig. 9—Cumulative incremental oil recovery in Mecca pilot.

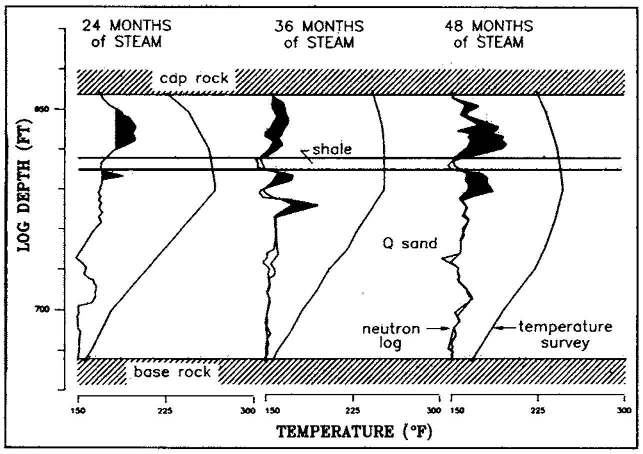

Fig. 10—Vertical sweep by steam (comparison pattern) in Bishop Observation Well T3, 70 ft from injector.

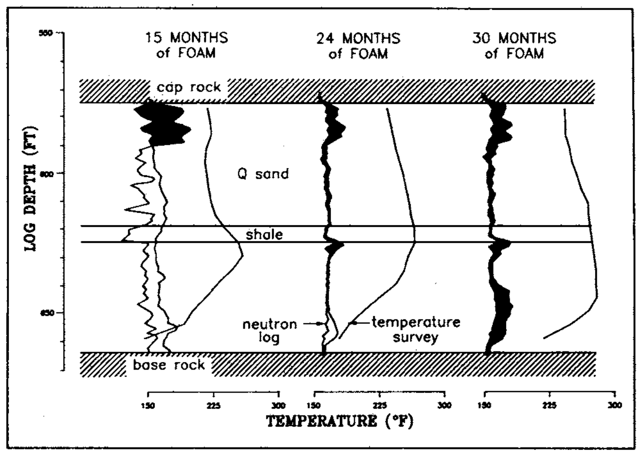

Fig. 11—Improved vertical sweep by steam foam in Bishop Observation Well T5, 70 ft from injector.

"Evaluation of the Bishop pilot was complicated by the steam soaks performed on old producers . . . and by the drilling of the two replacement and two infill wells."

that in the previous steamdrive; see the Appendix) coincided with a sharp temperature increase in an observation well, we inferred that the steam-foam front had passed this well.

Figs. 10 and 11 compare vertical distributions of gas saturation and temperature in the Bishop steam and steam-foam drives. Both observation wells are 70 ft [21 m] downdip from their respective injectors (see Fig. 1). The steam injector, Bishop Well 109X, was completed over the bottom two-thirds of Sand Q, and the foam injector, Well 94X, was completed full-interval. Because foam injection in Bishop was preceded by 1 year of steamdrive, the total time elapsed from the start of steam injection is about the same in Figs. 10 and 11. Note the gravity override by steam at Bishop Well T3 and the dramatic increase in vertical sweep resulting from steam foam at Bishop Well T5.

Fig. 12 shows a similar increase in vertical sweep at Mecca Well TT2, which is 90 ft [27 m] from the foam injector, Well 36X. The striking increase in the peak temperature (from 212 to 300°F [100 to 149°C]) seen here occurs within the perforated interval in Well 36X (the bottom 16 ft [4.9 m] of the Main M). The uniform temperature distribution at the far left of Fig. 12 resulted from 10 years of steam/condensate convection and downward heat conduction. A steam foam identical to that used at Bishop produced equally dramatic changes in vertical sweep in Unocal Corp.'s Midway Sunset pilot.[3]

Foam Growth Rate. Time-lapse analysis of the temperature surveys and neutron logs enabled us to determine the in-situ foam volume as a function of cumulative injection of the aqueous phase. The foam PV in **Fig. 13** was calculated as steam/foam-filled volume from the logs. If there was evidence that the injected brine could not reach certain intervals (Mecca's Upper Sand M), the steam volume in these intervals was subtracted from the foam volume. The average rate of foam-zone growth determined in this fashion is the same for the two Kern River pilots, a particularly useful result because this constant growth rate can be used to calibrate a foam simulation model.[4]

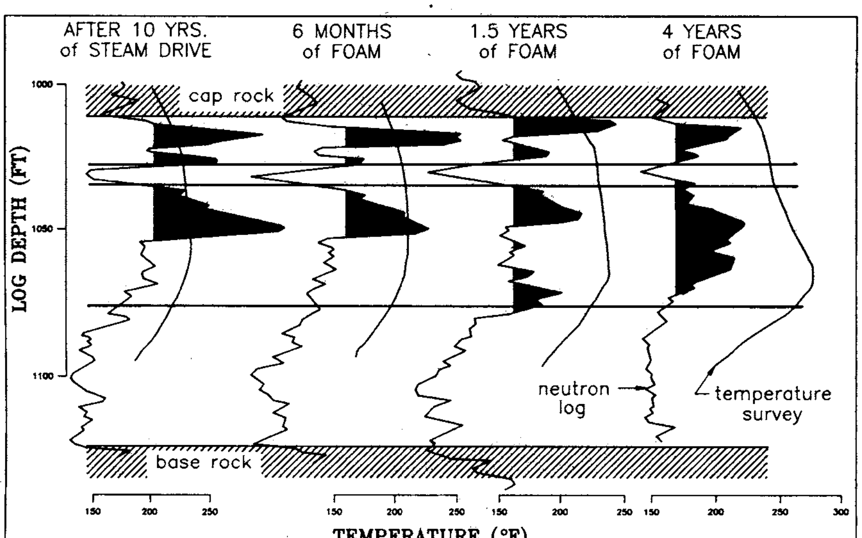

Fig. 12—Improved vertical sweep by steam foam in Mecca Observation Well TT2, 90 ft from injector.

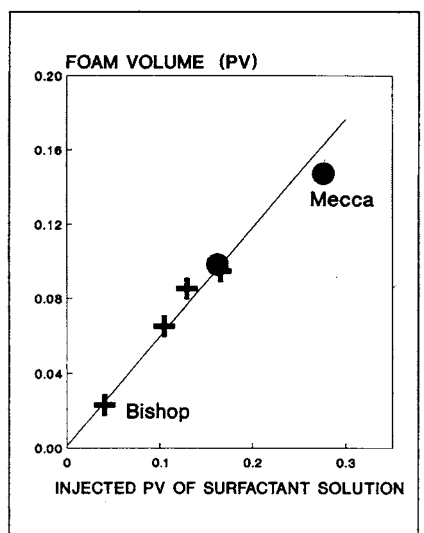

Fig. 13—Injected PV of surfactant solution in Mecca and Bishop pilots.

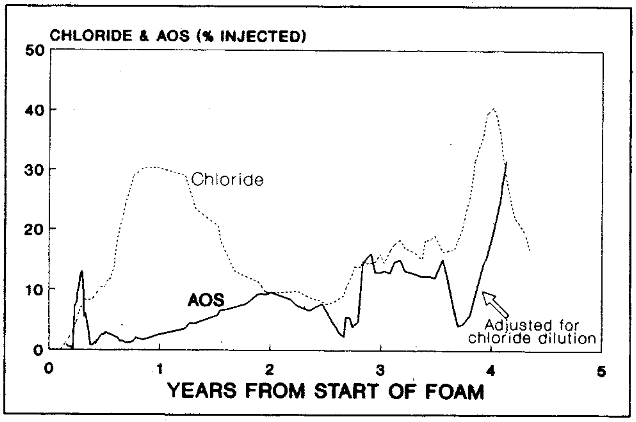

Fig. 14—Produced water analysis from confined producer Mecca Well 33A.

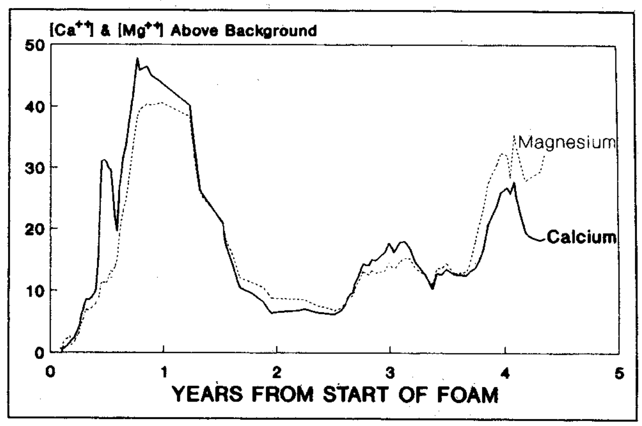

Fig. 15—Produced Ca^{++} and Mg^{++}, normalized wrt connate-water concentrations in confined producer Mecca Well 33A.

The constant volumetric growth of foam implies that the same mechanism controlled the foam generation and transport, irrespective of the particular surfactant brand, geologic differences, clay content, and drive maturity. Nominal downhole quality of the injected steam foam was 50% by mass. The corresponding volumetric foam quality was 99.7% of steam at 300°F [149°C]; i.e., the injected foam was very dry. Because there is no foam without a surfactant-rich solution, the foam growth was limited by the slower of the two propagation rates (i.e., that of the brine or the surfactant) **(Figs. 14 and 15)**. The brine propagated faster and exchanged sodium for the clay's calcium and magnesium. The surfactant was slower and never broke through (except for some thin, highly permeable layers, such as those in Mecca Well 33A). Quite probably, the foam growth was further slowed by inefficiencies in foam generation and bubble transport.

Just how slow was this foam growth? If the volumetric growth of steam foam in Kern River is expressed in terms of the injected volume of liquid, then 1 res bbl [0.159 res m^3] of steam foam was generated by about 1.5 res bbl [0.238 res m^3] of surfactant solution; meanwhile, 700 res bbl [111 res m^3] of steam zoomed through the foam zone.

ROS to Steam Foam. The ROS to steam foam was the same in both pilots; i.e., 10%. **Fig. 16** shows the ROS's in Mecca Well TT9 and Bishop Well T4, both 20 ft [6 m] from their respective injectors. The average ROS in both wells is similar to those reported[5,6] for steamdrives in the Kern River field; therefore, no ROS reduction resulted from the use of an AOS-1618 steam foam.

Apparent Foam Viscosity. The apparent viscosity of the gas phase in both pilots was calculated (see Appendix) from a model that treats the gas flow as radial with variable thickness, nonisothermal, compressible, and with condensation. **Fig. 17** presents the foam mobility-reduction factors (MRF) for Mecca and Bishop observation wells. The MRF's decrease away from the injectors and approach unity at the predicted foam fronts. More significantly, near the injectors, the in-situ MRF's agree well with laboratory values determined at similar flow conditions.

Project Economics. The decision to install a steam-foam project should depend only on the incremental profit to be made above the profit from a converted or terminated steamdrive. In this way, the foam project pays for the foam injectants, facilities, and any additional steam. Moreover, the more efficient

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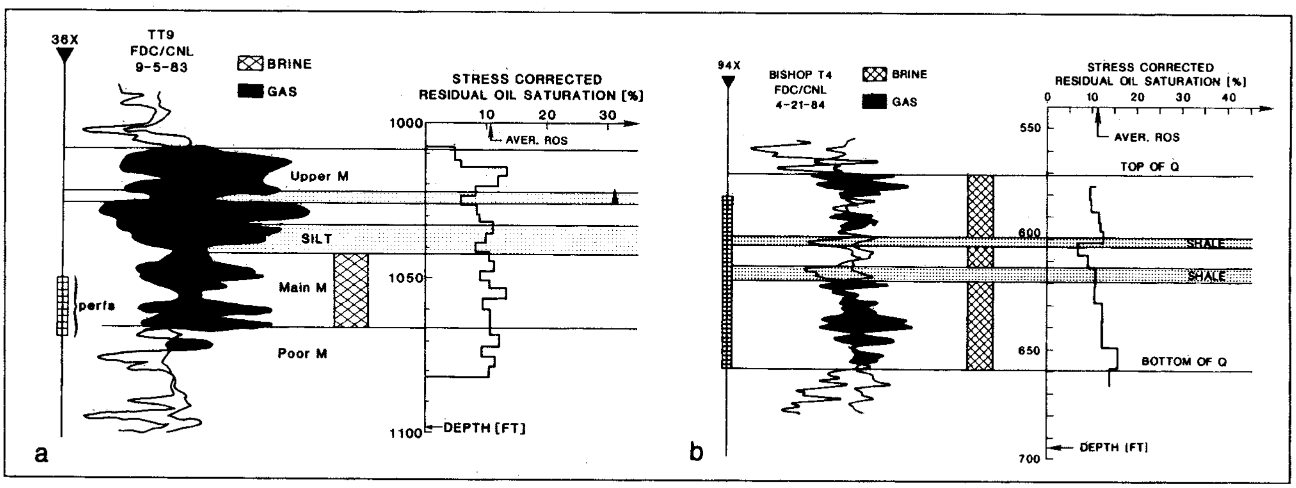

Fig. 16—Core results from (a) Mecca Well TT9 and (b) Bishop Well T4.

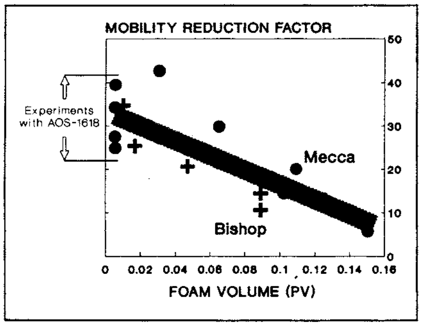

Fig. 17—Mobility reduction factors. Injected PV of AOS solution was 0.3 in Mecca and 0.2 in Bishop.

the competing steamdrive, the less oil (profit) remains for the foam to recover, regardless of the implementation.

Clearly, a full economic evaluation of the Kern River pilots is beyond the scope of this paper; however, from Table 4, it follows that in Bishop we used 10 to 15 lbm [4.5 to 6.8 kg] AOS-1618 per barrel of incremental oil. An effective surfactant cost (including salt, nitrogen, and foam-injection costs) of 80¢/lbm [$1.76/kg] is then equivalent to $8 to $12 per barrel of incremental oil. There were no other incremental costs; the steam would have been injected anyway, and we had no problems with surface facilities resulting from foam injection or surfactant production. Therefore, $8 to $12 per barrel is about the break-even oil price for the Bishop steam-foam pilot. A similar analysis for the Mecca pilot may be misleading because we cannot be sure that all its response resulted from steam foam.

Review

Following is a review of the Mecca and Bishop pilot results as one moves from the injectors toward the producers.

1. Major oil responses in both Kern River steam-foam pilots occurred after about 2 years of foam injection.
2. The confined Bishop pilot produced an incremental 8.5% OOIP (5.5% without infill wells) 5 years from the start of foam injection.
3. The unconfined Mecca pilot produced an incremental 14% OOIP 5 years from the start of foam injection. An additional 4% OOIP was produced after all injection was shut in, probably because of pressure blowdown and/or outside interference. A portion of the incremental oil production in the Mecca pilot resulted from gravity drainage, accelerated by surrounding Getty Oil Co. and Shell Western E&P Inc. steamdrives.
4. Foam conveyed some steam along the reservoir bottom, thus improving vertical sweep.
5. Foam-zone growth rates in the two pilots were similar; 1 PV of the foam was generated by 1.5 PV of injected surfactant solution.
6. The foam growth in the pilots was limited by the availability of surfactant in the aqueous phase.
7. The ROS to AOS-1618 foam is the same as that to steam (about 10%).
8. The apparent viscosities of steam foam in the two pilots were similar and decayed from 20 to 60 times as much as steam near the injectors down to steam viscosity at the predicted foam fronts. The near-injector viscosities agreed with laboratory values at similar flow conditions.

Nomenclature

- f = mass fraction of vapor in steam foam (foam quality)
- h = steam-foam zone thickness, ft [m]
- ΔH_C = enthalpy of condensation, Btu/lbm [kJ/kg]
- i_s = volumetric injection rate of steam, B/D [m^3/d] CWE
- k = permeability, md
- M = molecular weight, lbm/lbm mol [kg/kmol]
- p = pressure, psi [Pa]
- p_p = pseudopressure, psi-lbm/ft^3 [Pa·kg/m^3]
- $\dot{Q}_\ell$ = heat loss, Btu/D-ft^2 [kW/m^2]
- r = radius, ft [m]
- R = universal gas constant, Btu/(lbm mol-°F) [kJ/kmol·K]
- T = temperature, °R [K]
- T_S = saturation temperature, °R [K]
- u_f = superficial velocity of foam, ft/D [m/s]
- w_C = rate of vapor condensation, lbm/ft^3-D [kg/m^3·s]
- Y_p = pseudodistance, ft^{-1} [m^{-1}]
- z = compressibility factor
- λ = foam mobility, md/cp [m^2/Pa·s]
- $\bar{\lambda}_c$ = constant average foam mobility, md/cp [m^2/Pa·s]
- μ = viscosity, cp [Pa·s]
- ρ = density, lbm/ft^3 [kg/m^3]

Subscripts

- f = foam
- i,j = observation well numbers
- I = injector
- o = reference (injector)
- OB = observer
- s = steam
- st = stock tank
- w = water
- * = arbitrary reference condition

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References

1. Dilgren, R.E., Deemer, A.R., and Owens, K.B.: "The Laboratory Development and Field Testing of Steam/Noncondensible Gas Foams for Mobility Control in Heavy Oil Recovery," paper SPE 10774 presented at the 1982 SPE California Regional Meeting, San Francisco, March 24-26.
2. Dalton, R.L. Jr., Rapoport, L.A., and Carpenter, C.W. Jr.: "Laboratory Studies of Pilot Waterfloods," *Trans.*, AIME (1959) **219**, 24-30.
3. Mohammadi, S.S., Van Slyke, D.C., and Ganong, B.L.: "Steam-Foam Pilot Project in Dome-Tumbador, Midway-Sunset Field," *SPERE* (Feb. 1989) 7-16.
4. Patzek, T.W. and Myhill, N.A.: "Simulations of a Bishop Steam Foam Pilot," paper SPE 18786 presented at the 1989 SPE California Regional Meeting, Bakersfield, April 5-7.
5. Oglesby, K.D. *et al.*: "Status of the Ten-Pattern Steamflood, Kern River Field, California," paper SPE 8833 presented at the 1980 SPE/DOE Enhanced Oil Recovery Symposium, Tulsa, April 20-23.
6. Grease, G.R. and Schore, R.A.: "Steamflood Performance in the Kern River Field," paper SPE 8834 presented at the 1980 SPE/DOE Enhanced Oil Recovery Symposium, Tulsa, April 20-23.

Appendix—Estimation of In-Situ Foam Viscosity

We derive a model of foam flow that incorporates the usual well data (foam injection rate, pressure, and quality, temperatures, thickness of gas-filled intervals in observation wells, etc.) to calculate the average foam viscosity between a pair of wells.

Assumptions. Key assumptions of the model are that (1) the porous medium is homogeneous and isotropic (k is constant); (2) foam flow is radial and semisteady state; (3) heat losses from the reservoir are constant and known; and (4) the vertical interval of foam flow is a known function of radial distance, $h(r)$, obtained from neutron logs in the observation wells.

To find the foam mobility, we must solve the mass, energy, and momentum balances for the gaseous phase. The mass balance on water vapor in the foam is

$$-(1/r)(\mathrm{d}/\mathrm{d}r)(r\rho_s u_f)=w_C. \quad \text{(A-1)}$$

The overall mass balance on water is

$$-(1/r)(\mathrm{d}/\mathrm{d}r)(r\rho_f u_f)=0, \quad \text{(A-2)}$$

where the foam density, ρ_f, is calculated as

$$\rho_f=\frac{1}{\dfrac{1-f}{\rho_w}+\dfrac{f}{\rho_s}}\approx\frac{\rho_s}{f}. \quad \text{(A-3)}$$

The momentum conservation equation (Darcy's law) is

$$u_f=-\lambda(\mathrm{d}p/\mathrm{d}r). \quad \text{(A-4)}$$

The steam-foam temperature is equal to the saturation temperature at the pressure calculated from Eq. A-4; i.e., $T=T_S[p(r)]$. The rate of steam condensation, w_C, can be obtained from the energy balance:

$$w_C=2\dot{Q}_\ell/h(r)\Delta H_C. \quad \text{(A-5)}$$

The rate of heat losses from the reservoir, $\dot{Q}_\ell$, is assumed to be independent of radial position and known from an analytical expression or numerical simulation.

The superficial velocity of foam can be obtained by integrating Eq. A-2, with Eq. A-3 substituted for the foam density.

$$u_f(r)=[i_s\rho_{st}/2\pi h(r)][f(r)/r\rho_s(r)]. \quad \text{(A-6)}$$

From Eqs. A-1, A-5, and A-6, it follows that the steam quality is

$$f(r)=f_o-\frac{2\pi\dot{Q}_\ell}{i_s\rho_{st}\Delta H_C}(r^2-r_o^2). \quad \text{(A-7)}$$

Finally, the momentum conservation equation (Eq. A-4) is invoked.

$$\frac{i_s\rho_{st}}{2\pi}=-\lambda(r)\frac{\rho_s(p,T)h(r)}{f(r)}\frac{dp}{dr}. \quad \text{(A-8)}$$

Because the steam-foam temperature is equal to the saturation temperature, it is possible to define a *pseudopressure* function:

$$p_p(p)\equiv\int_{p^*}^{p}\rho_s[p,T_S(p)]dp$$

$$=\frac{M}{R}\int_{p^*}^{p}\frac{p}{zT_S(p)}dp. \quad \text{(A-9)}$$

Similarly, we can define a *pseudodistance*:

$$Y_p(r)\equiv\int_{r^*}^{r}\frac{f(r)dr}{f_oh(r)r}. \quad \text{(A-10)}$$

When applied to Eq. A-8, the transformations given by Eqs. A-9 and A-10 yield

$$i_s\rho_{st}f_o/2\pi=-\lambda(r)(dp_p/dY_p). \quad \text{(A-11)}$$

Because the left side of Eq. A-11 is constant, so is the right side, and the constant slope dp_p/dY_p makes foam mobility constant. In other words, if a line is drawn through each pair of points (Y_{pi},p_{pi}) representing the measured conditions at different wells, then the slope of the line gives a constant average mobility of foam between this pair of wells,

$$\lambda_{ij}=-\frac{\dfrac{i_s\rho_{st}f_o}{2\pi}}{\dfrac{\Delta p_{pij}}{\Delta Y_{pij}}}=\bar{\lambda}_{cij},\ i=0,1,2,$$

$$j=i+1, \quad \text{(A-12)}$$

where $\Delta p_{pij}\equiv p_{pj}-p_{pi}$ and $\Delta Y_{pij}\equiv Y_{pj}-Y_{pi}$.

The apparent viscosity of foam between each pair of wells is calculated as

$$\mu_{ij}=\frac{k_s}{\lambda_{ij}}=-k_s\frac{2\pi}{i_s\rho_{st}f_o}\frac{\Delta p_{pij}}{\Delta Y_{pij}},$$

$$i=0,1,2,\ j=i+1. \quad \text{(A-13)}$$

The pressure and temperature profiles between each pair of wells also can be calculated from Eqs. A-11 and A-12.

$$p_p[p(r)]-p_p[p(r_i)]=-\Delta p_{pij}/\Delta Y_{pij}$$

$$\times[Y_p(r)-Y_p(r_i)],\ r_i\le r\le r_j,\ j=i+1. \quad \text{(A-14)}$$

Because $p_p(p)$ is a monotonically increasing function of pressure, Eq. A-14 can be inverted to obtain the corresponding value of $p(r)$ and $T_S(p)$.

Calculation of Average *k* for Steam Flow in the Mecca Pilot. The average value of k_s in the Mecca pilot before steam-foam injection is found from a modification of Eq. A-13.

$$k_s=-\frac{\dfrac{i_s\rho_{st}w_o}{2\pi}}{\dfrac{\Delta p_p'}{\Delta Y_p}}, \quad \text{(A-15)}$$

$$\text{where } p_p'(p)\equiv\int_{p^*}^{p}\frac{\rho_s[p,T_S(p)]}{\mu_s[p,T_S(p)]}dp$$

$$=\frac{M}{R}\int_{p^*}^{p}\frac{p}{zT_S(p)\mu_s(p)}dp. \quad \text{(A-16)}$$

$Y_p(r)$ is given by Eq. A-10, $\Delta p_p'\equiv p_p'(p_I)-p_p'(p_{OB})$, and $\Delta Y_p\equiv Y_p(r_I)-Y_p(r_{OB})$. Note that the modified pseudopressure function (Eq. A-16) incorporates the known viscosity of steam.

In early 1980, the average injection rate in Mecca Well 36X was 270 B/D [43 m^3/d] CWE, steam quality was 0.57, downhole injection pressure was 24 psig [165 kPa], and average thickness of the steam zone was 27 ft [8.2 m] (from neutron log data in Wells TT1, TT2, and TT4 through TT6). With these parameters and $\dot{Q}_\ell$=41 Btu/D-ft^2 [3 kW/m^2], from analytical solution, $k_s\approx$ 930 md.

A laboratory measurement of permeability to steam in homogenized Kern River sand gave $k_s\approx$990 md.

SI Metric Conversion Factors

acres	× 4.046 873	E−01	=	ha
°API	141.5/(131.5+°API)		=	g/cm³
bbl	× 1.589 873	E−01	=	m³
ft	× 3.048*	E−01	=	m
°F	(°F−32)/1.8		=	°C
lbm	× 4.535 924	E−01	=	kg

*Conversion factor is exact.

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