Field Applications of Steam Foam for Mobility Improvement and Profile Control

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Summary

Foams are used to control and improve the injection profile in secondary or tertiary gas-injection processes and reduce gas mobility far from the injectors. Over the last decade, significant progress has been made in the understanding of the complex foam processes in porous rocks. The goal of this paper is to review consistently, albeit somewhat subjectively, several important field tests of foams, compare their performance, and critically evaluate the economic benefits from foam injection. It is shown that early, transient, and usually small oil production responses to surfactant injection are real, and depend critically on the reservoir architecture and gas flood implementation. These early production responses are related to the improvements of gas-injection profile by foam and are often quite profitable. The delayed, but bigger oil production responses are caused by foam propagation into the reservoir and could be very profitable, depending on the injection policy. An outline of an ideal future foam pilot is presented, and important advances in rigorous modeling of foam processes are discussed.

Introduction

Although there are eyewitness reports[19] of surfactant and air injection in Russia and China in the early sixties, the first documented field test of air foam was carried out in the Siggins field[8] (Oct. 1964 to March 1966). The first steam-foam test was conducted in a Kern River steamflood pilot[3] (Oct. 1976 to March 1977). Since then, there have been about 25 significant steam-foam projects (most of them listed and referenced in Ref. 19, Tables 1 through 4) and dozens of smaller commercial applications.[2] As of this writing, reports of nine CO_2 foam projects appeared in the literature.[19] Noncondensible gas foams are being used worldwide by service companies for well cleanup and stimulation.[19] A successful foam fracturing of a well in a pressure-depleted (subhydrostatic) reservoir has been reported in India.[19] Use of areated (foamed) drilling muds in areas of subhydrostatic reservoir pressures has also been reported.[19] In China, a noncondensible gas foam mixed with cement has been used successfully to block thief zones near water injectors.[19]

It is well known that the average bubble size in a foam controls its mobility.[7] Because of the limited space here and excellent reviews elsewhere,[7,10] I will omit the fundamental research on foam mechanisms and transport. Instead, I will compare several recent field tests of foams and point out their similarities, important differences, and lessons learned from them. I will try to avoid repeating already published materials. This paper is also a critique of the historical pilots and will end with a wish list for an "ideal" pilot in the future. Finally, I will summarize the current advances in modeling of foam flow in porous media.

Steam Foam

Background. Dozens of steam-foam projects have been implemented to do the following.

- Limit gravity override in flat and moderately thick reservoirs.
- Improve vertical sweep in massive and dipping reservoirs.
- Improve areal sweep and improve areal steam distribution.
- Inject steam into lower zones, otherwise unheated in thin and/or layered reservoirs.
- Improve injection profile, block thief zones, and reduce steam channeling.
- Improve heat distribution in steam soaks.
- Reduce residual oil saturation to steam.

Performance of these steam-foam projects was measured by the following.

- Mass of surfactant injected per unit volume of incremental oil.
- An increase of steam injection pressure.
- A redistribution of steam injection profile.
- A reduction of steam production rate and casing pressure.
- An improvement of vertical and areal sweep (reservoir desaturation and heating).

There are two approaches to enhancing heavy oil recovery with steam foam. Historically, the first one was to inject surfactant continuously for several years to propagate foam into the reservoir as far as possible and to displace oil. Good examples of this approach are the four-pattern Shell Mecca and Bishop pilots in Kern River[17] and Unocal Dome-Tumbador pilot in Midway Sunset (MWSS).[12] The two Kern River pilots were conducted in a moderately thick (27 to 30 m gross), slightly dipping (3°), and relatively uniform reservoir that suffered from a severe gravity override. Steam was injected either at the base or full interval. The Dome-Tumbador pilot was conducted in a massive (137 m gross), coarsely layered (three major zones), and dipping (16°) reservoir that also suffered from a severe gravity override. Steam foam was injected at the base of the bottom zone and steam leaked somewhat into the overlying two zones.

Another approach was to use foam to improve the steam injection profile. The best examples here are the Mobil Tulare pilot[4] and Chevron Sec. 26, Pattern 68BW, MWSS.[25] The Tulare pilot was conducted in Zones B and C of a finely layered, thick (61 m), and dipping (6°) reservoir that suffered from the nonuniform injection profile when steam was injected full interval. Finally, the Sec. 26 MWSS pilot was conducted in a thick (107 m gross), finely layered and dipping (20°) reservoir, with full-interval steam injection into 12 separately perforated intervals that spanned 70 m. Reservoir permeabilities varied greatly, but were as high as 2 μm^2 [2 darcy] in all the pilots.

The injector-producer distances varied from 46 m at Dome-Tumbador to 142 m in Tulare. The average rate of steam injection [in m^3/d of cold water equivalent (CWE) per injector] was 40 in Kern River, 87 in Dome-Tumbador, 111 in Tulare, and 80 in Sec. 26. Nominal steam quality was about 50% by mass at the wellhead. Tables 1 through 4 in Ref. 19 reveal other details.

Improved Injection Profile. Using krypton and sodium iodide as vapor and liquid tracers, respectively, in steam-foam injector 68BW, Chevron[25] confirmed that steam injection profile was improved by foam and that this improvement disappeared rapidly when surfactant injection was stopped. A longer-lasting profile improvement was reported for another injector in MWSS.[26] Although not measured directly, steam injection profile was vastly improved in another layered reservoir of comparable gross thickness (Mobil's Tulare), simply because no other plausible mechanism could account for the significant oil response.

For the single and/or partial injection intervals, such as in Shell's Mecca and Bishop and Unocal's Dome-Tumbador, the profile improvement is difficult to quantify and perhaps less important; steam flow in the reservoir is determined more by areal heterogeneities than the injector itself. However, even in a thin sand package (8 m), such as the Guadelupe field, a redistribution of foam injection profiles was noted in four wells.[13]

Increased Injection Pressure. In each of the tests mentioned above, a sustained 340 to 1700 kPa [50 to 250 psi] increase of downhole injection pressure was reported. With intermittent surfactant injection, steam-foam injectors sometimes failed to develop a significant pressure response.[4] As observed in Mecca,[17] a very strong

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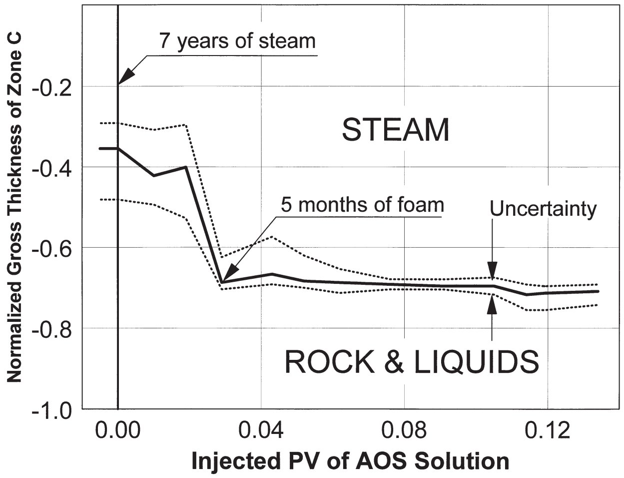

Fig. 1—A doubling of vertical sweep by steam foam in the Dome-Tumbador pilot.

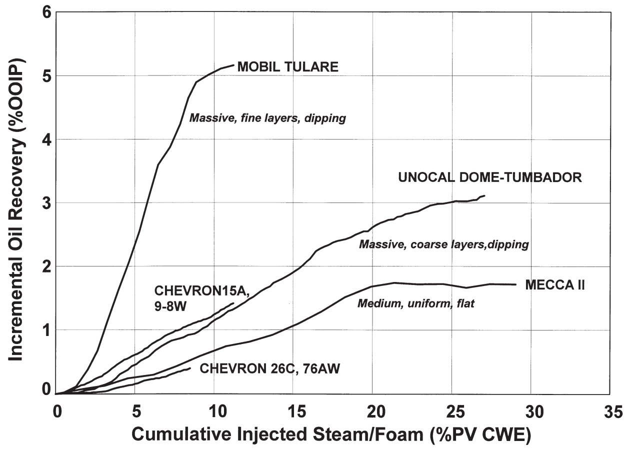

Fig. 2—Early production responses in several steam-foam pilots were almost instantaneous.

pressure gradient developed near a steam-foam injector, causing steam to flow spherically and invade accessible reservoir layers below the injection interval. However, very high injection pressure may not be desirable because steam injectivity decreases.

Improved Sweep. In all pilots that had observation wells, dramatic improvements of vertical sweep were detected with neutron logs and temperature surveys.

A 100% vertical sweep was observed in Mecca and Bishop as far as 27 m away from the injectors. In the same time frame, vertical sweep in a steamflood comparison pattern near the Bishop pilot[17] grew from 21 to 35% and then stopped.

Within 5 months of foam injection in Unocal's Dome-Tumbador, vertical sweep doubled from 35 to 70% some 27 m away from an injector (**Fig. 1**). An increase of areal sweep was also detected in a "blind-spot" observer.[12]

In Chevron's MWSS pilot, desaturation increased substantially 12 m from injector 68BW.[20,25]

In Mobil's Tulare, steam zones grew thicker[4]: up to 4.6 m over two-thirds of the pattern area in Zone B (steam thickness doubled) and up to 1.5 m over half the pattern area in Zone C. In addition, Mobil noted doubling of the areal sweep by steam.

Foam Propagation. The Kern River and MWSS pilots provided ample evidence of foam propagation far into the reservoir. There were many more logging observation wells in the Kern River pilots (eight at Mecca and seven at Bishop), than in Dome-Tumbador (two), and Sec. 26 (two). Time-lapse neutron logs in Mobil's Tulare observation wells (seven in Pattern 518) were not taken. Thus, it was possible to establish the average rate of foam growth in Kern River better than in any other field. For example, in Mecca, foam was propagated to a radial distance of 43 m from injector 36X in 4.5 years. Both in Mecca and Bishop, the reservoir volume filled with foam scaled linearly with the injected volume of surfactant solution (1 reservoir volume of foam was generated by about 1.5 volume of liquid surfactant solution). Therefore, foam propagated slower than surfactant. At Dome-Tumbador, only one observation well could be used to estimate the growth rate of foam. This rate was 2.5 to 3 times faster than that in Kern River, consistent with the ratio of cation exchange capacities in both formations.

In Sec. 26 of MWSS, foam broke through at an observation well 12 m from injector 68BW after 8 months of surfactant injection. If foam growth scaled linearly with the injected surfactant volume, then foam would have arrived at the second observation well, 21 m away from the injector, after at least 24 months of surfactant injection. Unfortunately, Chevron decided to shut off surfactant after only 18 months of injection and left this hypothesis untested. Chevron believed that foam stalled between the two observation wells. Unpublished* mechanistic simulations of the Sec. 26C pilot that accounted for the pressure gradient necessary to mobilize foam bubbles,[6,22] showed the foam stalling at about 15 m from the injector.

*Personal communication with F. Friedmann (July 1994).

Early Production Response. Fig. 2 shows that significant early production responses were observed in several steam-foam pilots. These responses were almost immediate and, therefore, had nothing to do with foam propagation in the reservoir. On the other hand, these responses were triggered by surfactant injection. The reasons for this unusual behavior are best explained by Unocal's Dome-Tumbador pilot. Three producers there, DT-1, DT-2 and T-7, were responsible for 75% of the incremental oil production during the first 6 months of foam injection.[12] Unocal took several temperature logs in the pilot producers. These rare logs could then be averaged over the perforated intervals, yielding average bottomhole temperatures (BHT's) as functions of time. A plot of oil rate vs. BHT in **Fig. 3** reveals that (1) all three wells were hot for a low-pressure steamflood in a high-permeability reservoir, (2) the wells cooled down by 11°C [20°F] during foam injection, and (3) there was a one-to-one correspondence between well productivity and the degree of cooling.

A hot producer vents steam that must be recovered through a casing vapor recovery system or back-pressures the wellbore. In fact, average downhole pressure in the three producers varied from 260 to 340 kPa [38 to 49 psia] and was equivalent to about 30 to 37 m of liquid in the wellbore.

For example, the equivalent liquid level in DT-1 was about 32 m before cooling and 23 m after cooling. The flow rate in a well producing by gravity drainage[15] is proportional to $h_r^2 - h_w^2$, where h_r is the maximum height of the oil column in the reservoir and h_w is that in the wellbore. Therefore, the production rate by gravity drainage is very sensitive to the wellbore pressure. For DT-1, $h_r = 35$ m is calculated for both limiting rates of oil production (16 and 24 m^3/d, respectively [100 and 150 B/D, respectively]) with reasonable

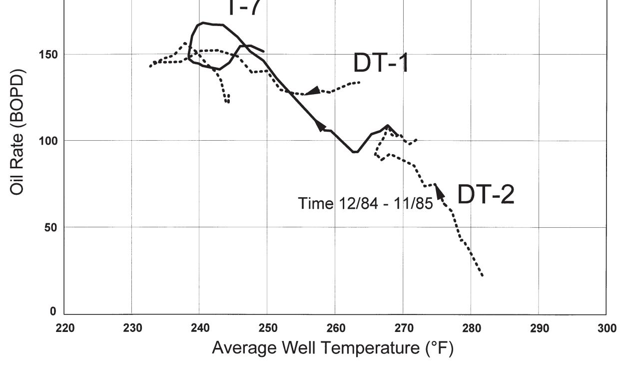

Fig. 3—Oil production vs. average BHT in three Dome-Tumbador wells follow an identical trend for almost 2 years.

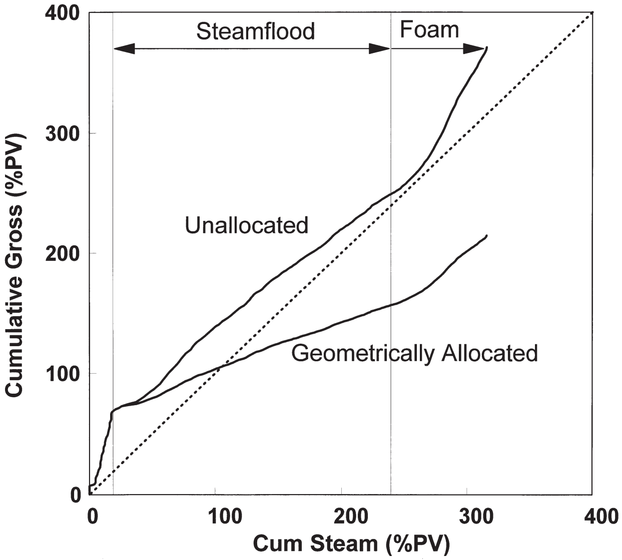

Fig. 4—Cumulative gross production in the Mecca steam-foam pilot vs. steam injection.

estimates of the average reservoir permeability to oil (0.7 μm^2), the "hotter" and "cooler" oil viscosity (5 and 10 cp), and the external radius of drainage (30 m). At the beginning of foam injection, a neutron log in observation well O-2, half-way between steam injector I-3 and the confined producer DT-2, showed $h_r = 46$ m. In the "blind spot" observation well, O-1, h_r was 18 m. A mean of these two oil column heights is 32 m, close to the calculated $h_r = 35$ m.

The producer cooling was caused by a reduction of steam inflow, as confirmed by the oil cut that tripled in DT-2 (from 0.15 to 0.45) after the start of foam injection.[12] Steam flow near the producers decreased because near the injectors steam pressure increased from 1380 to 2550 kPa [200 to 370 psia] because of foam. Therefore, the steam temperature increased from 193 to 227°C [380 to 440°F], and more of the hotter steam condensed, heating up the reservoir by 34°C, expanding the steam chest downward, and overcoming the additional heat losses. From published data,[12] one may estimate that it took at least 6 months to heat up Zone C to a new semisteady state.

In another MWSS pilot, four tomographic sections of Pattern 68BW after 2 (July 1989) and 15 (Aug. 1990) months of steam-foam injection,[20] paint a similar picture. In the reservoir layers heated by steam injected in 68BW, gas saturation decreased after 15 months of foam injection. This picture, however, is somewhat clouded by operational problems,[20,25] that substantially decreased the rate of steam injection in well 68BW in Aug. 1990. Still, the steam vent rate in the hottest producer, 68F, declined from 6 m^3/d [40 B/D] of 100% quality steam to less than 1 m^3/d [5 B/D] after foam injection; the casing pressure dropped from 240 to <136 kPa [35 to <20 psia]; the oil rate doubled; and oil cut increased from 0.05 to 0.2. One month after foam injection, the rate of heat injection increased from 1.8 to 2 MW [150 to 165 MMBtu/D], the allocated heat production decreased from 1.8 to 1.2 MW [150 to 100 MMBtu/D], and the oil rate increased from about 64 to 80 m^3/d [400 to 500 B/D]. This response, indicative of steam diversion by foam, declined with time, probably because of the lower heat injection rate in 68BW.

Similar responses were seen in the older steam-foam pilots with hot producers: Mecca, MWSS Pattern 9-8W, and MWSS Pattern 76AW (Fig. 2). In those wells in Pattern 9-8W that collectively doubled their oil production rate upon surfactant injection,[21] oil cut increased from 0.26 to 0.43. Conversely, in those wells that did not respond to foam injection, oil cut remained constant at 0.6. In Pattern 76AW, the three wells that doubled their oil production during surfactant injection also saw an increase of oil cut from 0.18 to 0.26. Conversely, oil cut decreased from 0.16 to 0.05 in the remaining wells that did not respond to foam.

No early production response was observed in Bishop after 1 year of steamflood, but oil producers there were relatively cold and back-

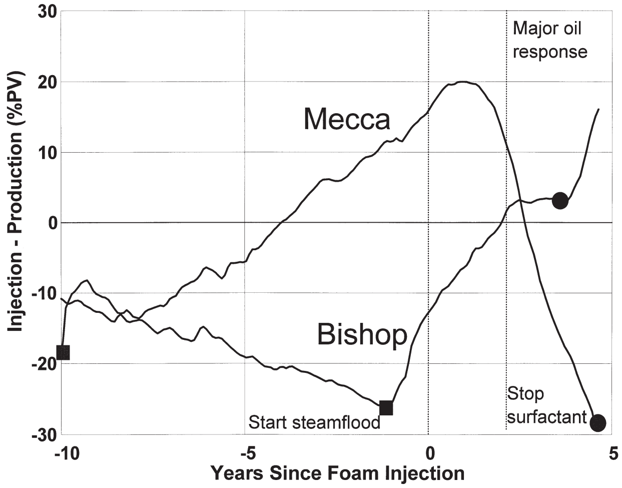

Fig. 5—Net liquid balance (Injection/gross production) for the Bishop and Mecca pilots.

pressured. Lack of thermal communication between the producers and injectors at Bishop was the reason for 13 steam soaks before foam injection.[17] Similarly, only two producers in the Chevron Sec. 26C pilot (68F and 68Z) were in good heat communication with injector 68BW, while the remaining nine producers were cold.[20,25] Obviously, if there is no heat communication, no early production response to foam injection can occur.

Lastly, the strongest initial oil production response was recorded in Mobil's Tulare. Initially, this production response resulted from an increased injection rate of steam (with foam). At this stage, oil production was merely accelerated. After approximately 6 months of foam injection, steam diversion resulted in incremental oil production. As in other early production responses, an overall oil cut in the pilot increased from 0.35 to 0.45 during surfactant injection,[4] and fell back to 0.35 within 2 months after surfactant was stopped. This behavior indicates strongly steam diversion by foam. Why was this diversion more important than in any other steam-foam pilot? Reservoir architecture seems to be the key. The South Belridge Tulare is a massive (137 m thick) set of discrete sand layers (Zones A through G in general, and A through E in Mobil's pilot), sandwiched between silts and shales that either are or are not continuous over a pattern area. A typical distribution of layer thickness in the South Belridge Tulare indicates that roughly half of the reservoir volume is distributed among the discrete layers that are less than 5 m thick. Mobil steamflooded only Zones B and C. Nevertheless, it is impossible to inject steam uniformly into every sand layer over a 61 m gross interval, whether limited-entry perforation, full-interval perforation, or multiple slim-hole injectors are used. Invariably, a few sand layers, usually at the top, receive most of the steam and become desaturated, while other sands remain cold. Therefore, steam foam serves as a means of redistributing steam injection more uniformly. In such an application, surfactant should be injected intermittently, just to keep the desaturated layers plugged with foam near the injectors. Moreover, steam vent rates and liquid levels in the producers should be monitored carefully. When the shale "baffles" leak, steam ultimately overrides and the effect of an improved injection profile is limited. On the other hand, as steam is forced to meander around these baffles, its areal sweep also increases. In the end, 1 lbm surfactant/bbl incremental oil in the Tulare pilot was money well spent, even under adverse economic conditions.

Late Production Response. A strong production response was seen after 2 years of foam propagation at Bishop and Mecca.[17] In Dome-Tumbador, the decreasing steam injection rate, limited lift capacity and/or high casing pressures might have curtailed the late production response.[12] No such response was seen in any other steam-foam pilot. In Tulare, foam propagation was not an objective, and surfactant injection lasted for only 13 months. In Sec. 26C, pattern 68BW was mostly cold and a small volume of injected steam foam was insuffi-

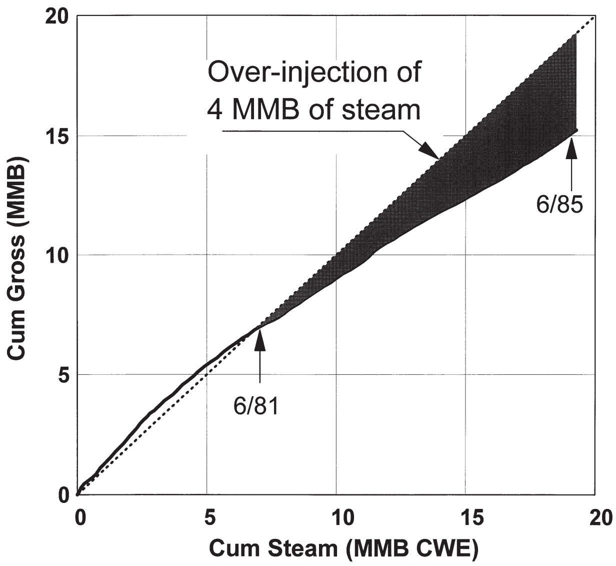

Fig. 6—Cumulative gross production in the Dome-Tumbador pilot vs. steam injection.

cient to make a significant difference. On the other hand, as will be shown below, even in those pilots where the late production response was seen, there were many problems with quantifying it.

Mecca Steamflood and Foam Pilot. The four-pattern steam-foam pilot in Mecca Lease, Kern River, was initiated in June 1980, after 10 years of an unconfined steamflood.[17] More than 3 PV of steam was injected and 3.8 PV of liquids produced in the pilot (**Fig. 4**). In its first 10 years, the Mecca pilot was unconfined, the steam chest extended updip far beyond the pilot area, and gravity drainage contributed significantly to production. In Sept. 1980, Getty Oil Co. started high-rate steamfloods along the northern, western, and southern border of the Mecca lease. After 1983, a steamflood initiated in the Rambler Q sand, east of Mecca, likely interfered with the pilot. The steamfloods around the Mecca lease partially confined the pilot by increasing the average reservoir pressure. As a result, the total area of oil drainage toward the pilot producers extended even farther beyond the pilot boundary. The net liquid balance (injection-unallocated gross production) for the Mecca pilot is shown in **Fig. 5.** The initial desaturation of 18% PV agrees well with an average 4 m of desaturation estimated from neutron logs in seven pilot wells in April 1970. Similarly, with a neutron log estimated desaturation of 30% at the beginning of the foam drive and a 15% overinjection of steam, Fig. 5 suggests that approximately 45% of steam injected in the Mecca pilot (1.35 PV) migrated updip. With an average cumulative-oil/steam ratio (COSR) = 0.2, about 0.3 PV of oil produced in the pilot [38% original oil in place (OOIP)] resulted from gravity drainage. The ultimate oil recovery within the geometrical area of the pilot was then about 71% OOIP. A major oil production response, observed in Mecca after 2 years of foam injection, was estimated to be 14% OOIP.[17] It remains unclear what portion of this response, if any, was caused by the gradual confinement of the pilot by the surrounding steamfloods. If the oil production response at Mecca were scaled in proportion to the overall gravity drainage from updip, then an incremental 8.7% OOIP would result, more in line with the Bishop pilot.

Bishop Steam-Foam Pilot. In Aug. 1982, a steam-foam drive was installed in the Bishop pilot[17] after only 1 year of steam injection and 15 years of steam soaks. As opposed to Mecca, the Bishop pilot was always confined. Desaturation at the beginning of the steamflood was about 25%, agreeing well with an average 5.2 m of gas saturation in the three pilot injectors drilled in 1981. Fig. 5 shows several major differences between the Shell pilots. After 1 year of foam at Mecca, the net injection there reached a maximum, after which the gross production greatly exceeded the injection. In contrast, Bishop was always overinjected. The major production re-

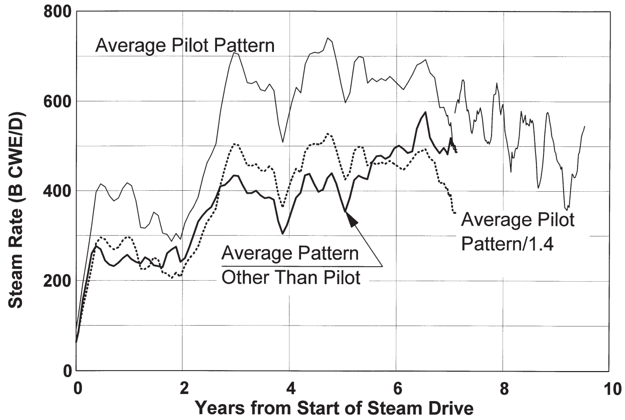

Fig. 7—Average steam injection rate per pattern in the Dome-Tumbador pilot and the nonpilot patterns.

sponse to foam and two replacement and two infill wells merely arrested the overinjection for almost 2 years. Because steam foam also increased vertical sweep at Bishop, the overinjection problem there was even worse than suggested by Fig. 5. Most likely, increasing the lift capacity of the pilot producers would result in more oil production. If so, then the four new wells simply lessened the imbalance of injection and production, and the estimated[17] oil response to foam, 8.5% OOIP, was conservative. This estimate coincides with an incremental oil displaced by steam foam predicted by a simple foam transport model.[18]

Dome-Tumbador Steamflood and Foam Pilot. Unocal initiated a 17-pattern steamdrive in early 1978 in Dome-Tumbador leases, Sec. 23 of MWSS. Producer casing vents were closed, back-pressuring the injectors and resulting in a high steam chest pressure. Steam injection exceeded gross rate since mid-1981 (**Fig. 6**). The total overinjection totaled 640 000 m^3 [4 million bbl] CWE and resulted in a low COSR (0.22 in 1985). Four interior steamdrive patterns were converted to a steam-foam pilot in Jan. 1985. Between Jan. 1978 and Dec. 1984, steam injection rate in these four patterns was 40% higher than in the remaining ones (**Fig. 7**), exacerbating problems with overinjection. Because of the higher steam rate, the pilot area had not been symmetrical with respect to the adjacent steamdrive patterns; hence, the geometrical allocation underestimated production there. The usual accounting procedure for oil produced in a project is based on periodic well tests, later allocated to balance the total oil shipped from that project. Such an allocation may fail to account for the differences in pattern performance. In Oct. 1984, Unocal started to measure oil production from the pilot area independently using a separate tank and accurate testing method.[12] This commendable procedure provided a unique opportunity of comparing the allocated production with the actual one. The two sets of production data overlapped between Oct. 1984 and April 1985 and the lease-al-

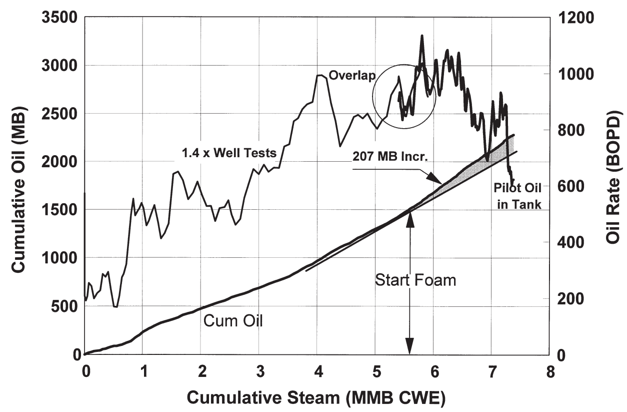

Fig. 8—Oil rate and cumulative oil produced in the Dome-Tumbador pilot vs. cumulative injected steam.

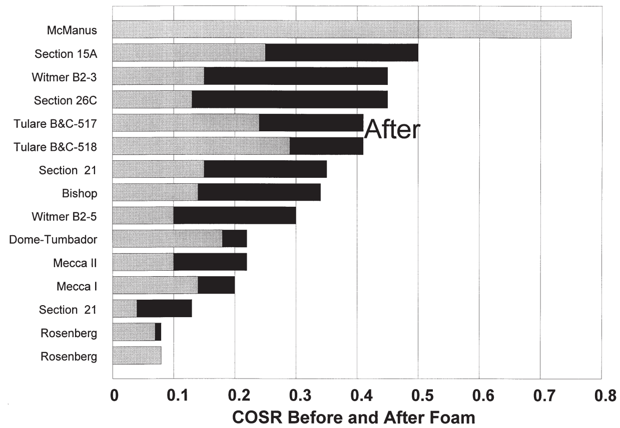

Fig. 9—Cumulative oil steam ratio just before and after injection of steam foam.

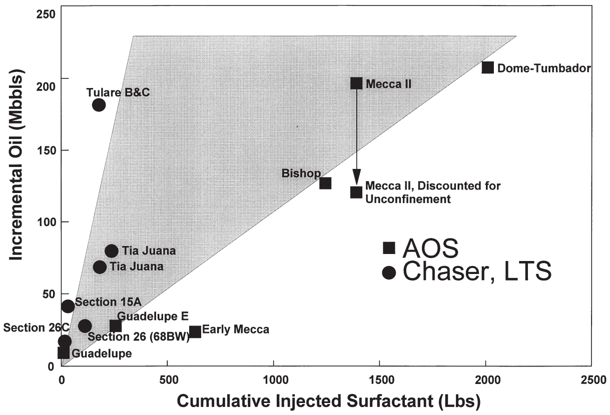

Fig. 10—Cumulative incremental oil vs. cumulative injected mass of surfactant.

located data fell 40% below the pilot data for the nine pilot producers (**Fig. 8**). This proves the importance of a separate production facility for an oil-in-the-tank pilot (to my knowledge, this was the only steam-foam pilot that had such a facility). Because the steam injection rate and oil production both declined during foam injection, the incremental oil was calculated here as an increase of the slope of cumulative oil recovery vs. the cumulative injected steam (Fig. 8). The incremental oil thus calculated was 33 000 m^3 [207,000 bbl], significantly more than the incremental 21 500 m^3 [135,000 bbl] estimated by Unocal[12] relative to a steamflood decline curve that was quite uncertain in view of the volumetric imbalance of the pilot.

Because oil production from massive dipping sands, such as Dome-Tumbador, is completely dominated by gravity drainage, problems with casing pressures and/or lift capacity may overwhelm the benefits of foam propagation and the resulting desaturation of the reservoir. As an aside, we still do not know if a strong negative effect of the diminishing liquid head for gravity drainage can be offset by an additional heating of oil and a small viscous pressure gradient, both resulting from foam. If the decreasing rate of gravity drainage cannot be overcompensated by the increased oil mobility, then steam foam should not be used in massive, dipping reservoirs, where a well-designed steamflood and gravity drainage can do the job efficiently, achieving an ultimate oil recovery of 70% OOIP. The 2D, vertical cross-section simulations with a simple foam model[18] suggest that, in a steeply dipping (40°) and thick reservoir (91 m), the late response to steam foam is small (72 vs. 70% OOIP recovery), if producers in all patterns remain pumped off. Otherwise, the incremental mobilized oil bypasses the producers.

Increased Oil/Steam Ratio. In all projects listed in Ref. 19, Tables 1 through 4, significant increases of the cumulative oil steam ratio were reported after foam injection (**Fig. 9**). Therefore, in all these cases, foam managed to divert steam to where it had not been, regardless of the production responses that depended on many other factors (proper well testing, heat communication, wells pumped-off, etc.).

Different Surfactants. The surfactants used to generate steam foams fall roughly into three categories: alpha olefin sulfonates (AOS's), linear toluene sulfonates (LTS's), and Chevron chasers. The most striking difference between these surfactants and the projects they served is shown in **Fig. 10**, where the total incremental oil production is plotted vs. the total injected mass of active surfactant. The two historical approaches to foam injection are now obvious. On one hand, we see the massive amounts of injected AOS that led to plenty of incremental oil (Mecca, Bishop, Dome-Tumbador), but at a high surfactant-to-incremental-oil cost. On the other hand, we see much smaller amounts of LTS's and Chevron chasers (Tulare, MWSS) used to improve the injection profile and recover less oil, but at a lower surfactant unit cost. The glaring exception is the Mobil Tulare pilot that recovered as much oil as Mecca, but with $^1/_{10}$ of the surfactant mass.

Bottom Line. There is plenty of evidence that steam foam recovers additional oil *if* there is heat communication between the injectors and producers (even if steam is available, steam-foam surfactants are usually poor foamers at lower temperatures). It is less certain, however, what portion of this oil is incremental and not a mere acceleration of production. Or perhaps it does not matter because the economic benefits of an accelerated oil production are derived from the technical merits of the process (less cumulative steam, less overhead, etc.). From this point of view, the steam-surfactant injection strategy is most important (i.e., inject at a high rate early and reduce the rate later).

It seems certain that in finely layered and thick reservoirs, a foam can divert steam to the otherwise bypassed layers. What happens to the steam once it enters these layers depends on the vertical and areal heterogeneity of a particular reservoir. It appears that it is impossible to inject steam into all deserving reservoir layers in Tulare and the Monarch sands in MWSS.

It seems less obvious that steam foam should be used in massive and dipping sands that are dominated by gravity drainage. The same reasoning might hold for the moderately thick, "almost" homogeneous reservoirs, such as Kern River. On the other hand, in a flat and not-so-thick reservoir, gravity drainage is slow and difficulties with recirculating the overlain steam are severe. If steam foam can desaturate such a reservoir effectively and cheaply, then it is worth considering.

"Ideal" Pilot. Implementation of a meaningful steam-foam pilot is difficult, intricate, and expensive (see Ref. 1). On the basis of industry experience to date, an ideal future pilot might have the following features.

1. The pilot consists of several patterns and is confined if possible (4 interior patterns inside a 16-pattern project seem to be a reasonable minimum).
2. There is a separate well-testing and oil tank facility for the pilot and surrounding patterns.
3. There are multiple observation wells in all pilot patterns, in different directions and at different distances from the injectors.
4. There is a control pattern (or patterns) with its own observation well(s), which is very difficult in practice.
5. The reservoir geology and its initial state are known.
6. All wells are in sound shape and clean, the producers are pumped-off, a production trend is established and stable, and there is approximate balance between injection and gross production.
7. Injection profiles in the pilot are known.
8. There is heat communication between the injectors and most of producers (if not steam soaks should help).
9. There are accurate and computerized injection control and pump monitoring systems.
10. There is a reasonable logging, reservoir imaging, and fluid sampling program.
11. There is a commitment to run the pilot for a reasonable period of time (based on simulations) and then some.

12. There is a single engineer in charge of the pilot for its duration, as well as a plan and manpower to interpret the pilot results fully and in a timely fashion.

There are very few companies that can do it all internally and, therefore, field pilots should be joint ventures with clearly defined contributions, responsibilities, and time lines. If these conditions cannot be met, then it is probably better and cheaper to base business decisions on a reasonable reservoir description and numerical simulations of the competing processes. These simulations may then be followed by small-scale field demonstrations, such as the CO_2 foam tests by Mobil.[19] A rigorous, mechanistic model of the foam processes should help in lowering the field testing costs considerably by allowing the properly scaled "what-if" simulations.

Foam Models

The flow of foams in porous media has been modeled in several ways, with (1) a mechanistic bubble population balance[5,9,16]; (2) a semiempirical mass balance of surfactant with one,[18] or several adjustable parameters[14]; and (3) a fractional-flow "limiting capillary pressure, P_c, model."[23] The mechanistic models that account for the evolution of foam texture and, hence, gas mobility in situ,[7] coupled with basic research on foam flow in single and multiple pores[10] and foam/rock/oil interactions,[10,11] have made rigorous simulations of foam flow in one[5] and three dimensions[9] feasible. More research on foam trapping and mobilization,[22] surfactant design, and surfactant degradation in the reservoir is still needed to complete these models. However, even today, mechanistic simulations of steam-foam pilots are possible.[6] Because it is rigorous, the population balance method is capable of scaling up a laboratory description of foam to the field. Likewise, owing to its high resolution, the population balance method should prove useful in evaluating whether near-wellbore treatments can be enhanced by foam.

The semiempirical models account for the presence of foam by a reduction of gas permeability when surfactant is also present. Usually, *ad hoc* expressions have been developed for gas relative permeability as a function of surfactant concentration in the aqueous phase, oil saturation,[14,18] and capillary number.[14] Although successful in predicting the incremental oil recovery at Bishop, these models must be calibrated with the average growth rate of foam in a comparable field test (Mecca) and do not scale properly from one field to another. Somewhat more rigorous, but still quite limited, is the fractional flow model that recognizes the limiting role of capillary pressure in foam coalescence.[23,27] Because it is inherently 1D, the limiting P_c model cannot be applied to the field. Its extension to three dimensions has led[24] to yet another semiempirical expression for gas relative permeability.

Conclusions

Foams are widely used to improve the injection profile of a gas and/or reduce its mobility inside a reservoir. There have been over 25 successful tests of steam foam, some of them major pilots, and dozens of small commercial applications.

Performance of seven different steam-foam pilots was critically evaluated in the paper:

1. In all cases, the steam injection pressure increased significantly and the COSR also increased, relative to the preceding steamflood.
2. Vertical and areal sweep by steam foam also increased.
3. In several pilots with hot producers, an immediate oil production response to surfactant injection was noted. This response was caused by a temporary reduction of steam flow into the producers, which was caused by a higher pressure and temperature steam foam near the injectors. The producers would then cool down and be less backpressured by steam in the casing.
4. All early production responses resulted in higher oil cuts and less vented steam.
5. Late oil production responses were observed in only two pilots in Kern River and occurred after 0.4 PV of surfactant injection.
6. In finely layered and thick reservoirs, foam can divert steam to the otherwise bypassed layers.
7. It is less obvious that steam foam should be used in massive and dipping sands (MWSS Dome-Tumbador) that are dominated by gravity drainage.
8. In a flat, moderately thick reservoir (Kern River), gravity drainage is slow and difficulties with recirculating the overlain steam are severe. If steam foam can desaturate such a reservoir effectively and cheaply, then it should be considered.
9. Larger volumes of AOS's injected to propagate foam in Kern River and Dome-Tumbador resulted in larger volumes of incremental oil, but at a higher surfactant-to-incremental oil cost. Smaller volumes of LTS's and Chevron chasers used only to improve the injection profile recovered less oil, but at a lower surfactant unit cost.
10. The Mobil Tulare steam-foam pilot recovered as much oil as Shell's Kern River Mecca, but with $^1/_{10}$ the surfactant mass. This outstanding performance was caused by the fine layering of the Tulare sands and, consequently, the inability to sweep them with steam alone.

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SI Metric Conversion Factors

bbl	$\times 1.589\ 873$	$E-01 = m^3$
cp	$\times 1.0^*$	$E-03 = Pa \cdot s$
ft	$\times 3.048^*$	$E-01 = m$
$^\circ F$	$(^\circ F - 32)/1.8$	$= {}^\circ C$
md	$\times 9.869\ 233$	$E-04 = \mu m^2$
psi	$\times 6.894\ 757$	$E+00 = kPa$

*Conversion factor is exact.

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