A Two-Phase Flow-Splitting Device That Works

Jeff Jones, SPE, and **R.L. Williams,** SPE, Santa Fe Energy Resources Inc.

Summary. Laboratory and field tests of wellhead steam quality have shown that typical methods of regulating phase distribution are unsatisfactory. This paper describes a successful project to develop a distribution device that is economical to install and yields the desired phase split.

Introduction

For many years, Santa Fe Energy Resources (SFER) has designed steam distribution systems with "dead-end" tees, as Hong[1] recommended. Field tests of wellhead steam quality have shown this method of regulating phase distribution to be unsatisfactory; laboratory tests confirmed field observations. Thus, a project was begun to develop a distribution device that could be retrofitted into existing systems or installed in new systems and would yield the desired phase split. This paper reports on laboratory testing and field demonstration of this device.

Background

Since the inception of steam EOR, liquid/vapor-phase distribution in piping systems has been a serious problem. Specifically, the ratio of the phases leaving the two downstream branches (**Fig. 1**) in a typical side-branch tee junction rarely matches that of the upstream branch. Fouda and Rhodes[2,3] first documented this phenomenon, and Oranje[4] and Hong[1] brought it to the attention of the petroleum industry. Others[5-14] have attempted to improve the situation with various levels of success. Their solutions have had deficiencies ranging from a very limited operating range to high capital and operating costs.

Hong[1] suggested the most economical solution—a dead-end tee configuration (**Fig. 2**). Subsequent laboratory testing by Thonsgaard,[14] Azzopardi *et. al.*,[15] and SFER (plus field measurements in existing steamflood systems) showed good phase-distribution efficiency at a 50% mass flow split with a rapid falloff in efficiency at unequal branch flows.

Theory

It has been long observed that secondary flow currents develop in fluids flowing around pipe bends. **Fig. 3** shows these secondary currents as double-helical spins. The higher-velocity core fluid, motivated by its higher momentum, moves to the outside of the bend, subsequently displacing low-energy fluid nearer the no-flow boundary layer to the inside of the pipe bend in the helical flow pattern. In two-phase annular flow, such as that in steam distribution systems, Anderson and Hills[16] observed liquid buildup on the inside portion of the pipe bend (Fig. 3). From this, Johansen[17] postulated that a pipe tee will perform as a pipe bend. Thus, at some point, fluid flowing in a side branch will develop a double-helix pattern with profound phase-separating impact.

Thonsgaard[14] observed this effect in laboratory studies with pipe tees. **Figs. 4 and 5** show this observation as an explanation of why side-branch tees experience severe phase separation through the entire operating range and discontinuous liquid flow direction at about 15% vapor flow rate in the branch (**Fig. 6**). These helical flow patterns develop quickly and are dominant by 15% side-branch vapor flow, forcing virtually all the liquid phase to the inside of the bend and down the branch. Below 15% flow, fluid-column momentum is enough to force the liquid to stay in the main branch.

The dead-end tee suffers from the same secondary-current problem, as **Fig. 7** shows. **Fig. 8** plots laboratory data and field measurements for the 31-injector steamflood system in **Fig. 9.** In Fig. 8, an equal split is obtained only at nearly equal branch flow rates for both laboratory and field data. **Fig. 10** shows results of a laboratory test and demonstrates that a side-branch tee with a dividing wall performs essentially the same as a dead-end tee.

New Design

An investigation was started to design a distribution tee that would allow installation of an economical piping network, as in Fig. 1, yet yield good phase splits.

The laboratory setup is not described in detail here because of the excellent correlation of four very different studies shown in Fig. 6. Oranje[4] studied full-sized gas system piping; Thonsgaard[14] and Hong[1] used ⅜-in. pipe; and SFER used ½-in. PVC pipe. Our laboratory setup was identical to Hong's Fig. 1[1] except for the ½-in. pipe. **Table 1** lists the flow conditions used in all tests. Figs. 6 and 8 show results of our tests with side-branch and dead-end tees, respectively.

These studies provided convincing evidence that a successful flow splitter must do its work before the flow reaches the branch. The widely variable and overpowering flow dynamics within the branch typically narrows the effective range of any flow-splitting device to a specific flow condition. Thus, a successful design must have the following features.

1. The phase should be thoroughly mixed before entering the flow splitter.
2. The split must be made upstream of the branch.
3. The flow area should be chambered to control development of dominant secondary flow.
4. The split flows must be kept separate thereafter.

Fig. 11 shows details of the resulting design.[18] In operation, flow first reaches the conventional static mixer and exits as a homogeneous mixture. The mixer design chosen also imparts a powerful and consistent directional momentum to the flow as it approaches the flow stratifier. This section provides several vertical layers of alternating flow-division chambers designed to prevent establishment of the detrimental secondary flow currents so pronounced in full pipe flow. Finally, a dividing wall guides the divided flow to its appropriate downstream leg. **Fig. 12** shows the performance of this device in a laboratory test.

Observations During Laboratory Testing

One interesting fact emerged during the laboratory phase of this project: it appears that trends in two-phase flow distribution are simply additive. **Fig. 13** depicts our first observance of this. Curve A shows the results from laboratory runs with a static mixer upstream of a side-branch tee with a dividing wall. Curve B is for a tee with no static mixer but with the wall and stratifier. With some artistic license used to extend these curves, Curve C is the result of bisecting the distance between Curves A and B normal to the equal gas/liquid split line. Curve D is a plot of results from an actual laboratory run combining all the various pipe elements.

Fig. 14 shows results of a subsequent test of this observation. Curves A and B show results of a couple different physical configurations chosen because they seemed to add to a desired result. Curve C is a theoretical average of the first two runs, and Curve D is an actual laboratory run of a tee with the two elements.

Field Testing

Fig. 9 is a schematic of the piping network serving 31 wells in a 155-acre steamflood.[19] This project is laid out in a conventional

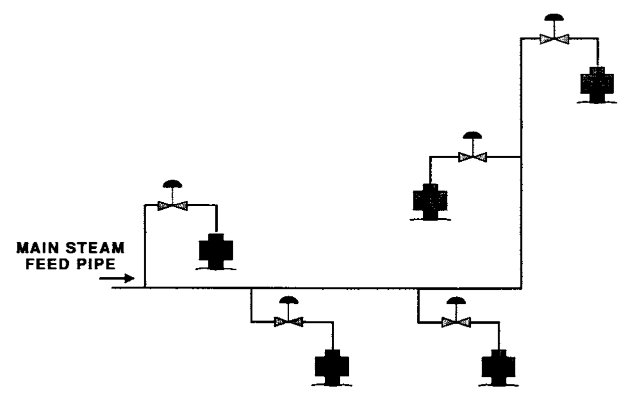

Fig. 1—Side-branch tee steam distribution system.

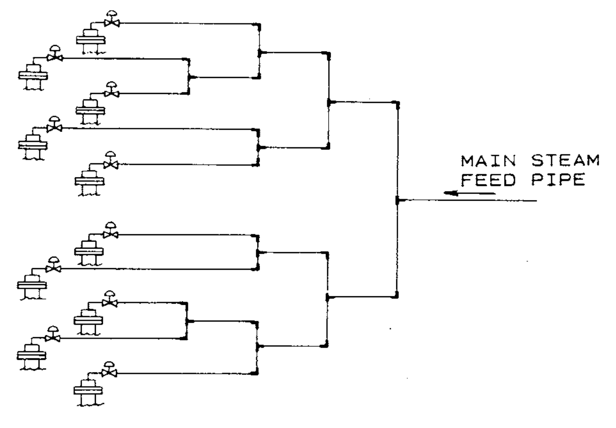

Fig. 2—Dead-end tee steam distribution system.

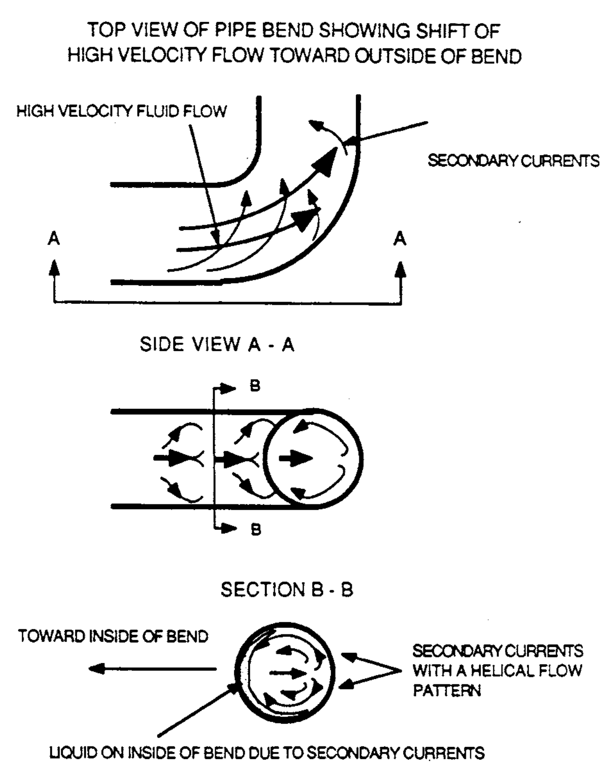

Fig. 3—Secondary currents in a pipe bend.[14]

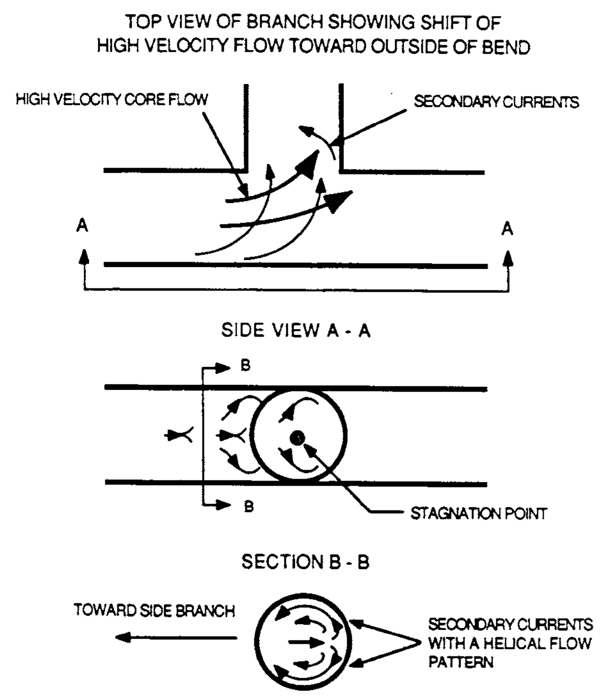

Fig. 4—Secondary currents in a pipe tee.[14]

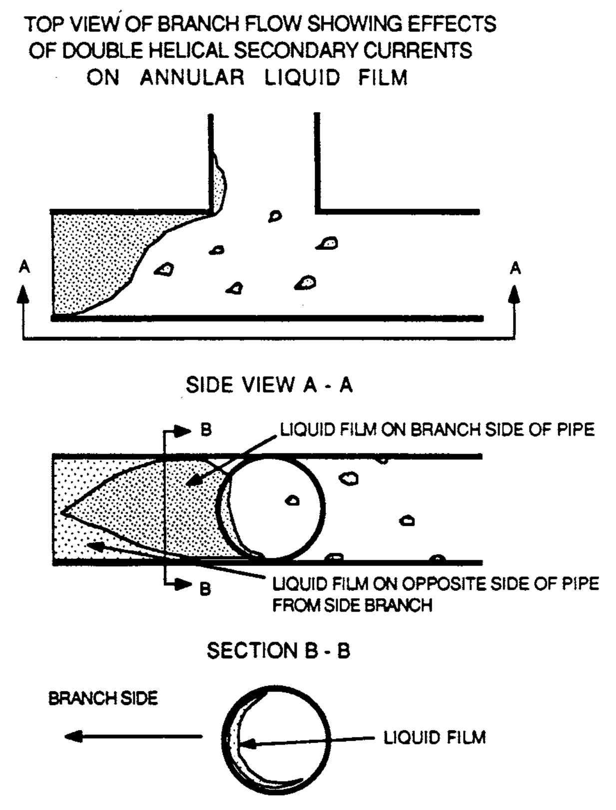

Fig. 5—Effects of secondary currents on annular flow.[14]

5-acre inverted-five-spot pattern and has been in operation since Jan. 1986. When started, it used state-of-the-art technology, including dead-end tee manifolding in the distribution system for quality control[1] and limited-entry perforations in the injectors for mass-flow-rate control.[20]

A 1988 fieldwide check of wellhead quality showed that this system was unsatisfactory. **Table 2** lists the test results. Thus, a field

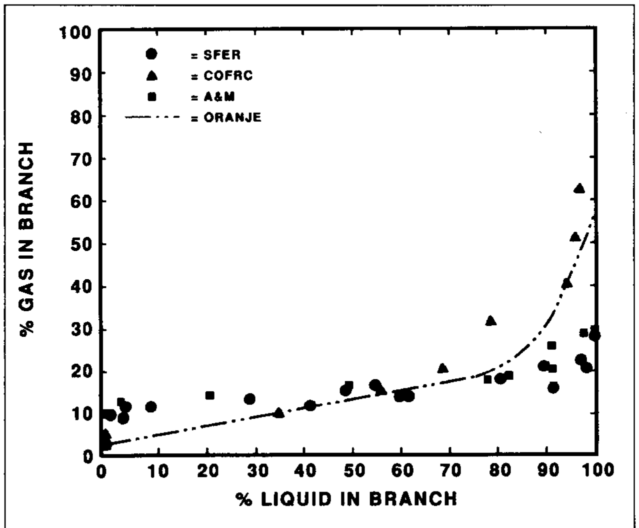

Fig. 6—Side-branch tee performance from four investigators.

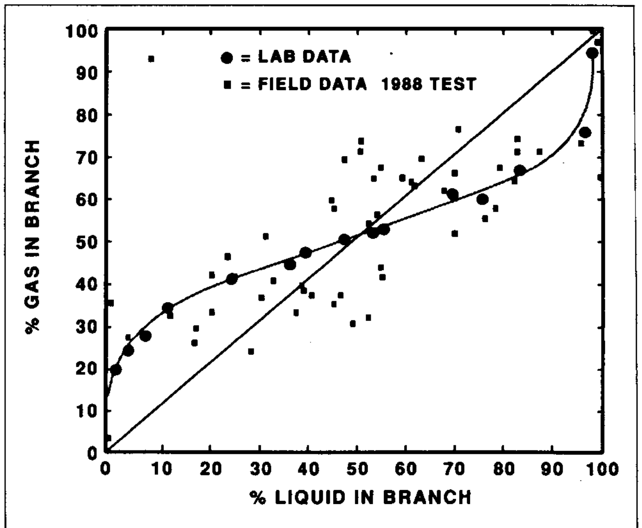

Fig. 8—Dead-end tee performance tests.

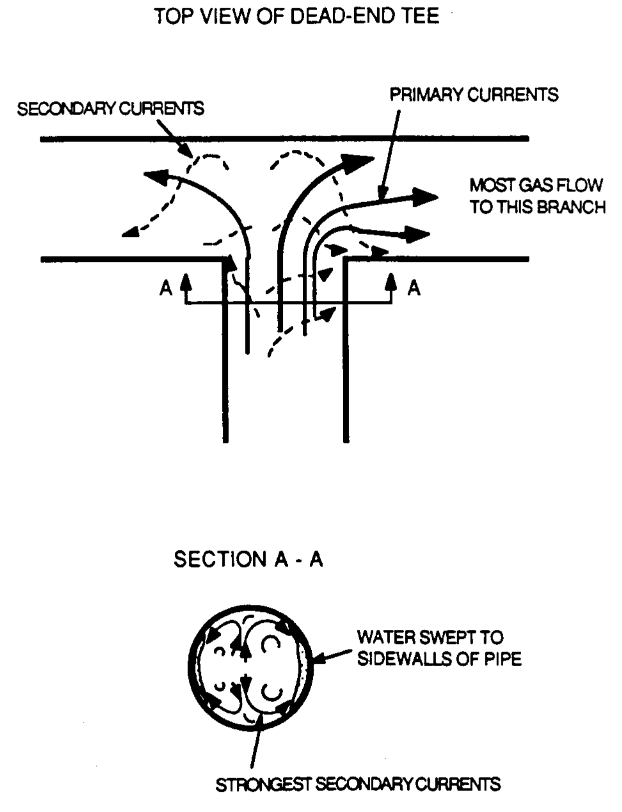

Fig. 7—Flow configuration for dead-end tee with secondary currents.[14]

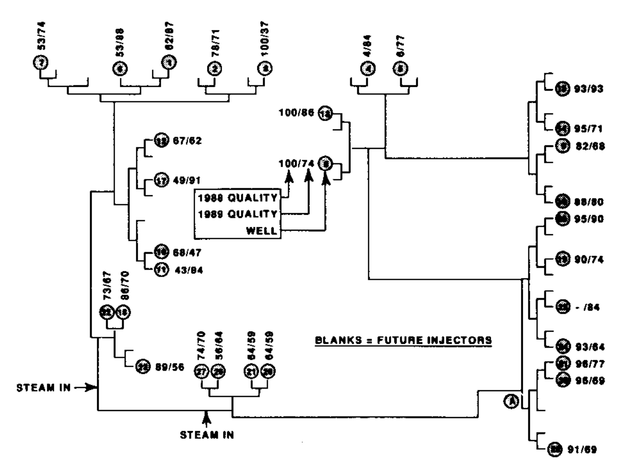

Fig. 9—Schematic of field steam distribution with "before" and "after" steam quality.

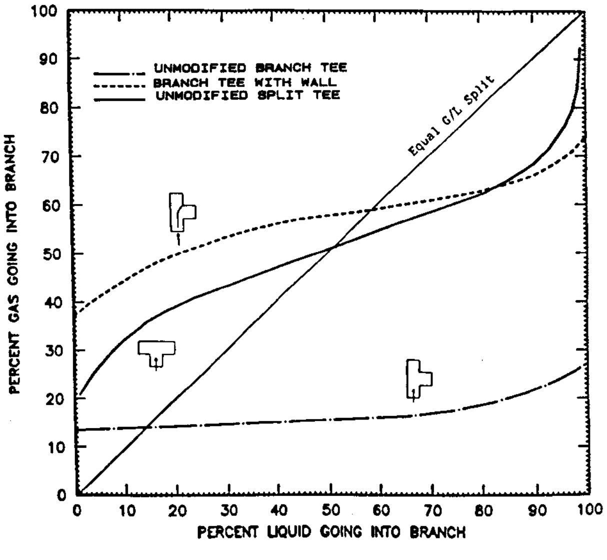

Fig. 10—Laboratory results showing that dead-end tee does not perform well over wide range.

trial of the new distribution tee was formulated, beginning with a single 12-in. tee in location A in Fig. 9. Pipe sizes in this network vary from 3 to 12 in. This was a severe test of the unit because only three wells are serviced from this branch, and a 6-ft vertical rise exists in the pipe just past the split. This combination of conditions resulted in virtually 100% quality steam injection in these three wells. **Table 3** shows the great improvement in quality distribution across the test tee, although individual wells still received poor-quality distribution because the other division points still were conventional pipe fittings.

With this encouraging test, we rebuilt the entire system, including 45 tees covering every split and adjustable flow chokes on each injector. Table 2 includes results of a 1990 flow and quality test

TABLE 1—FLOW CONDITIONS FOR FOUR FLOW-SPLITTING TESTS

	Hong[1]	Oranje[4]	SFER[18]	Thonsgaard[14]
Pipe ID, in.	⅜	3	½	⅜
Gas velocity, ft/sec	140	23	98	90
Liquid rate, cm^3/min	50	50	83	10
Pressure, psig	6	440	6	—

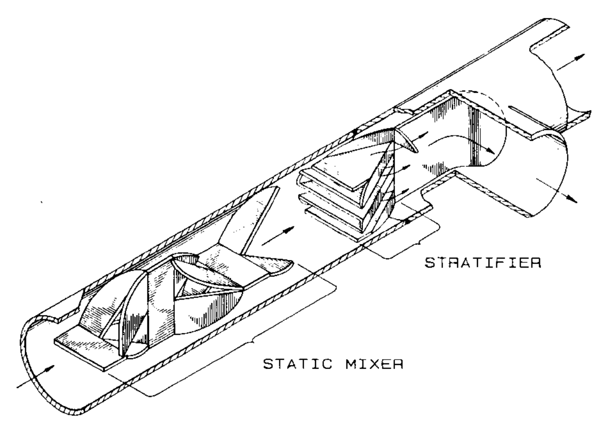

Fig. 11—New steam distribution tee.

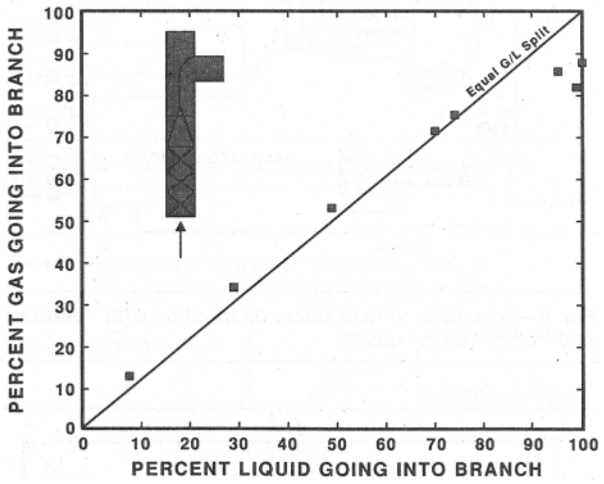

Fig. 12—Laboratory performance of new tee.

run after this installation. This test was run with the chokes wide open to prejudice the comparison of before and after results as little as possible.

Test Results

Statistical analysis of both tests showed a significant performance improvement with these devices. **Fig. 15** is a composite of four histograms showing steam-quality-control tendencies at each well and node. The nodes include all wells plus all tees. The quality and flow rate at the unmeasured upstream nodes were calculated by tracking vapor and liquid flows back from each well. **Fig. 16** shows an overplot of quality vs. injection rate of both tests for the 31 wells plus standard deviation bars for each. All the above analyses showed a marked improvement in quality and flow as a result of the tees. In the former case, only eight wells received steam of 60% to 80% quality, with 72% being design. Two wells at the end of the system received >600 BWPD, while 13 wells received +90% quality steam.

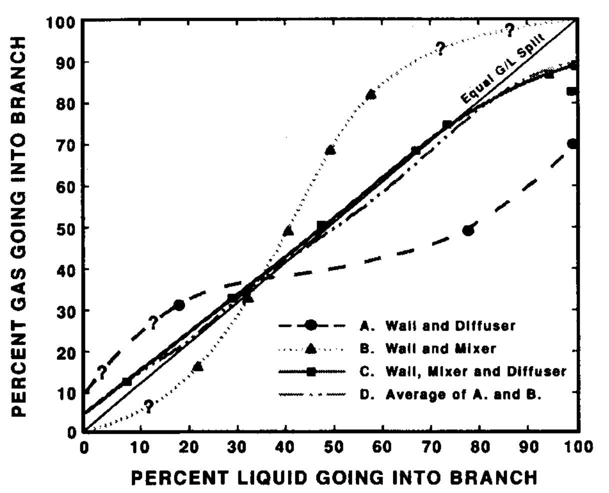

Fig. 13—Composite results of three tests showing additive phenomenon.

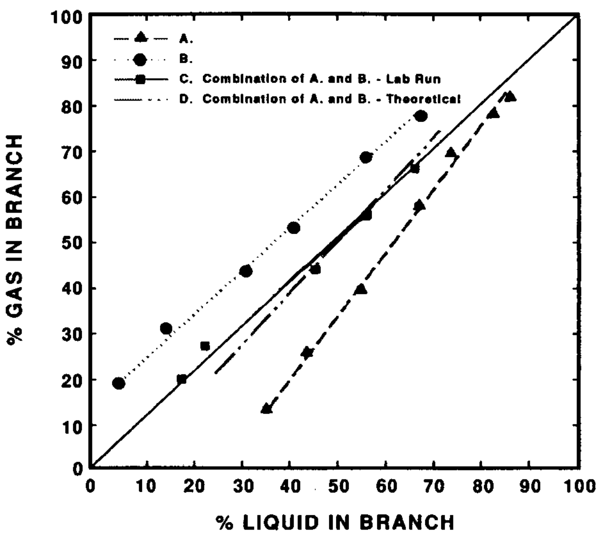

Fig. 14—Second example of additive phenomenon.

With the tees, 16 wells received 60% to 80% quality steam. All but two wells received +50% quality steam. Those two low-quality wells also had low injection rates, indicating downhole mechanical trouble rather than distribution problems. This was confirmed in subsequent workovers on the two injectors. No well took more than 400 B/D steam.

A critical parameter in the field application of this device is maintenance of a minimum threshold fluid velocity exceeding 25 ft/sec. Device effectiveness decreases below this velocity. In existing systems, the line size in the tee split may have to be reduced to achieve adequate velocity.

Economics

The total cost to install 45 tees of 3- to 12-in. diameter and 31 surface chokes was $150,000. The tees accounted for about $80,000 of the total. Fabrication took 4 months; installation took 4 days with several welders to minimize downtime.

Determination of payout was complicated by several major operational problems associated with the fact that the steamflood zone overlies an actively operated diatomite reservoir. **Fig. 17** plots steamflood performance, and the instability of the steam injection rate reflects these operational problems. Fluid withdrawals from the diatomite were causing severe surface subsidence measured in

TABLE 2—DATA FOR STEAM-INJECTION WELL

Well	Flow Rate (B/D) 1988	Flow Rate (B/D) 1989	Steam Quality (%) 1988	Steam Quality (%) 1989
1	425.3	258.7	62.1	87.1
2	453.9	287.7	78.1	71.1
3	19.1	95.4	100.0	36.8
4	600.7	94.1	4.2	84.5
5	727.4	229.9	6.3	77.3
6	301.4	193.7	52.7	88.2
7	398.6	204.5	53.4	74.0
8	247.2	308.8	100.0	73.5
9	283.5	248.3	81.6	67.9
10	365.1	276.4	88.3	80.5
11	530.1	195.6	43.2	83.5
12	188.3	187.8	66.5	62.1
13	379.4	148.5	100.0	86.6
14	199.3	322.2	95.1	71.0
15	293.8	245.1	93.4	93.3
16	251.3	169.3	68.3	47.1
17	507.5	311.1	48.5	90.7
18	486.3	308.4	85.7	70.3
19	278.7	292.7	89.9	74.3
20	113.0	63.0	95.1	39.9
21	478.8	289.8	64.6	58.7
22	276.0	236.3	72.7	67.3
23	256.1	339.4	89.0	56.8
24	226.7	181.4	93.3	64.6
25	Shut in	306.9	Shut in	84.0
26	432.2	244.3	56.2	63.5
27	333.5	302.2	73.7	70.1
28	395.9	381.7	63.8	58.9
29	308.9	255.1	91.3	68.5
30	251.3	254.6	95.6	68.5
31	397.9	219.0	95.8	77.3

TABLE 3—RESULTS OF INSTALLATION OF PILOT 12-in. TEE AND ALL TEES

Well	Steam Quality (%) No Tee	Steam Quality (%) With One Tee	Steam Quality (%) With All Tees
29	91	83	69
30	96	59	69
31	96	50	77
Average	94	65	71

feet per year. The result was a slip plane within the Tulare interval and frequent well failures. Recent initiation of a waterflood in the diatomite zone has slowed surface subsidence significantly. Another problem was a concentrated development program in the underlying diatomite zone, which required steam injectors near the drilling wells to be shut down.

Even with these problems, the project experienced measurable improvement in performance. We attributed a conservative 200 B/D of the increased production to the tees. The steam/oil ratio also appears to have improved. Oil was about $13/bbl during 1989–90. If an average total lift cost of $5/bbl is assumed, payout occurred in just 2 months.

It is apparent from Fig. 17 that modifications were at least partly instrumental in improving operation over the last one-half of the project life.

Conclusions

1. In two-phase flow, conventional pipe elements suffer from strong dynamic secondary-flow phenomena, which tend to separate gas and liquid phases, precluding equal phase distribution.

2. Unequal phase distribution, although severe, has been shown to be predictable and stable in both small-scale laboratory and full-sized piping systems.

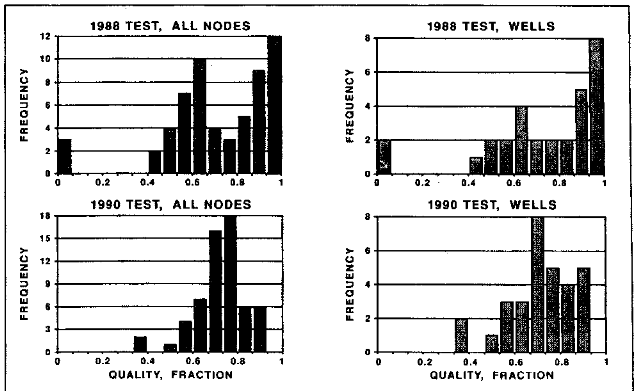

Fig. 15—Histobar graphs of "before" and "after" tee performance in a field application.

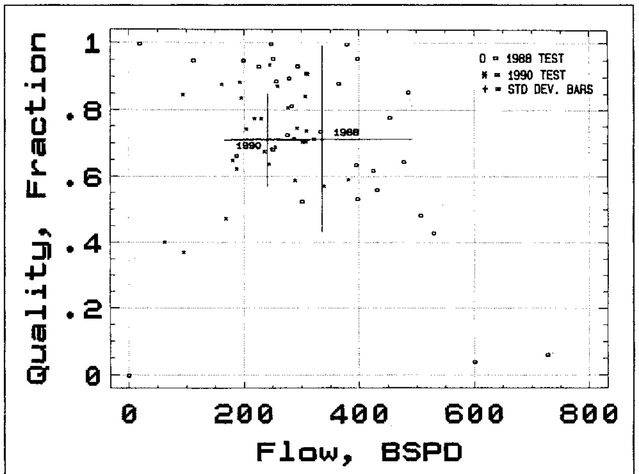

Fig. 16—Crossplot of flow vs. quality at the wellhead showing improved performance with new tees.

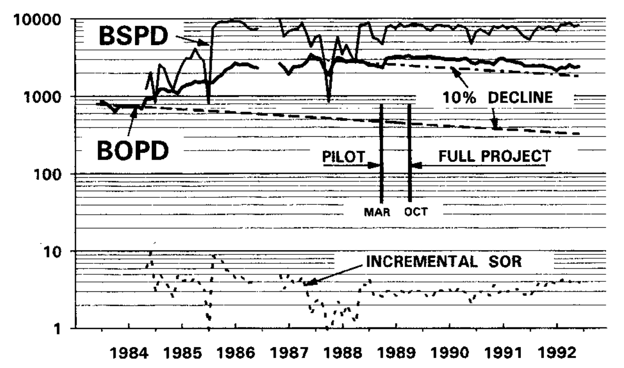

Fig. 17—Performance of the Tulare steamflood showing improvement from installation of modified tees.

3. A simple, passive, and inexpensive device has been designed, built, and demonstrated to produce excellent performance in a field system.

Acknowledgment

We thank SFER for permission to publish this paper.

References

1. Hong, K.C.: "Two-Phase Flow Splitting at a Pipe Tee," *JPT* (Feb. 1978) 290; *Trans.*, AIME, **265.**
2. Fouda, A.E. and Rhodes, E.: "Two-Phase Annular Flow Stream Division," *Trans.*, Inst. Chemical Engineers (1972) **50,** 353.

Authors

Jones

Williams

Jeff Jones is a senior staff engineer at SFER in Bakersfield. He holds a BS degree in mechanical engineering from California State U., Fresno. He holds several patents for oilfield equipment. A member of the Editorial Review Committee, Jones also is active in local SPE section activities. **Rik Williams** is a division engineer for production for SFER. He previously was a reservoir and a production engineer with Getty Oil Co. An author or coauthor of more than 20 technical and economic papers, Williams has served on several committees. He holds a BS degree from Cornell U., MS and engineer's degrees from Stanford U., and an MBA degree from California State U., Bakersfield.

3. Fouda, A.E. and Rhodes, E.: "Two-Phase Annular Flow Stream Division in a Simple Tee," *Trans.*, Inst. Chemical Engineers (1974) **52,** 354.
4. Oranje, L.: "Condensate Behavior in Gas Pipelines is Predictable," *Oil & Gas J.* (July 2, 1973) 39.
5. Hardy, T.P.: "T Coupling for Pipes," U.S. Patent No. 172,117 (Jan. 11, 1876).
6. Hurley, T.F. and Dickinson, R.: "Apparatus for Dividing or Combining Streams of Fluent Materials," U.S. Patent No. 2,094,948 (Oct. 5, 1937).
7. Ohlswager, S., Edison, R.R., and Dresser, T.: "Liquid-Vapor Distributor," U.S. Patent No. 3,899,000 (Aug. 12, 1975).
8. Godbey, J.K.: "Process and System for Providing Multiple Streams of Wet Steam Having Substantially Equal Quality for Recovering Heavy Oil," U.S. Patent No. 4,396,063 (Aug. 2, 1983).
9. Jensen, J.C.: "Two-Phase Flow Splitter," U.S. Patent No. 4,516,986 (May 14, 1985).
10. Konak, A.R.: "Method and Apparatus for Splitting Two-Phase Flow at Pipe Tees," U.S. Patent No. 4,522,218 (June 11, 1985).
11. Konak, A.R.: "Method and Apparatus for Splitting Two-Phase Flow at Pipe Tees," U.S. Patent No. 4,574,827 (March 11, 1986).
12. Aggour, M.A. and Greebe, F.: "Method and Apparatus for Splitting Two-Phase Gas-Liquid Flows Having a Known Profile," U.S. Patent No. 4,574,837 (March 11, 1986).
13. Leech, C.A., Rancudo, T J., and Groman, J.W.: "Steam Distribution Manifold," U.S. Patent No. 4,505,297 (March 19, 1985).
14. Thonsgaard, J.E.: "Controlling Two-Phase Flow Through Pipe Junctions," MS thesis, Texas A&M U., College Station (1989).
15. Azzopardi, B.J., Purvis, A., and Govan, A.H.: "Annular Two-Phase Flow Split at an Impacting T," *Intl. J. Multiphase Flow* (1987) **13,** No. 5, 605.
16. Anderson, G.H. and Hills, P.D.: "Two-Phase Annular Flow in Tube Bends," *Multi-Phase Flow Systems,* Inst. Chemical Engineers Symposium Series, Inst. Chemical Engineers Services, London (1974) **2,** No. 38, 1.
17. Johansen, S.E.: "Experimental Study of Gas-Liquid Flow in a Pipe Tee," MS thesis, U. of Tulsa, Tulsa, OK (1979).
18. Jones, J.A.: "Device for Uniformly Distributing a Two-Phase Fluid," U.S. Patent No. 4,824,614 (April 25, 1989).
19. Spivak, A. and Muscatello, J.A.: "Steamdrive Performance in a Layered Reservoir—A Simulation Sensitivity Study," *SPERE* (Aug. 1987) 324.
20. Small, G.P.: "Steam Injection Profile Control Using Limited-Entry Perforations," *SPERE* (Sept. 1986) 388.

SI Metric Conversion Factors

acre	×	4.046 873	E−01	=	ha
bbl	×	1.589 873	E−01	=	m^3
ft	×	3.048*	E−01	=	m
in.	×	2.54*	E+00	=	cm
psi	×	6.894 757	E+00	=	kPa

*Conversion factor is exact.

SPEPF

Original SPE manuscript received for review Feb. 7, 1991. Revised manuscript received April 23, 1993. Paper accepted for publication May 13, 1993. Paper (SPE 21532) first presented at the 1991 SPE Annual Technical Conference & Exhibition held in Bakersfield, Feb. 7–8.