Improved Well Stimulation with Limited Entry Treatment[1]

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ABSTRACT

In Texas and New Mexico this company has experienced excellent results from an improved well stimulation method called "limited entry treatment." This treatment is accomplished by (1) limiting the number of perforations in a well and (2) providing sufficient injection rate to require the restricted flow capacity of the perforations to divert the treatment to a greater portion of the perforated interval. This method has proven to be more effective than has any other method in diverting treating fluids to multiple horizons.

From December 3, 1960, to January 1, 1962, 201 wells have been treated by this technique. The initial production performance of wells treated by limited entry completions is superior to that of conventional treated wells. Gamma ray tracer logs indicate most of the pay is being treated even though not covered by perforations. The limited entry technique has been successfully used in treating two separate reservoirs simultaneously in dually completed wells. Results of these simultaneous treatments have been gratifying in both well performance and reduced costs.

GENERAL REVIEW OF MULTIPLE ZONE TREATMENT

Conventional Treatment Techniques

The efficient simultaneous treatment of multiple porous intervals in a reservoir has been a long standing problem in well stimulation; and with greater or lesser degrees of effectiveness various methods have been used to treat multiple zones. The bridge plug and packer method is effective, but is relatively expensive; further, the injection rates are considerably reduced, and it is

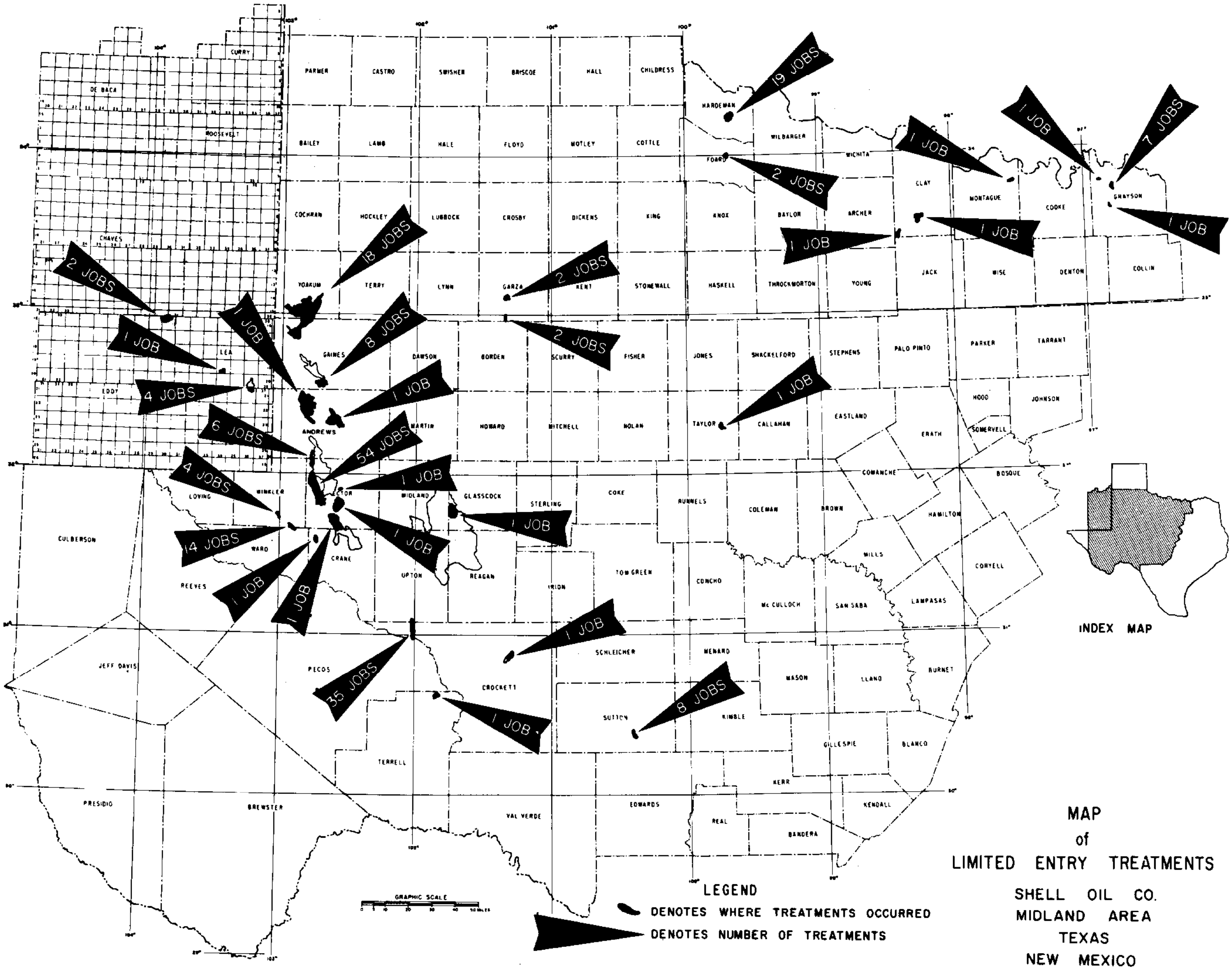

FIGURE NO. 1 DEC 3 1960 to JAN. 1, 1962

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sometimes mechanically hazardous. Too, temporary plugging agents to divert the treatment have been used with apparent success, but the main disadvantage of temporary plugging agents such as moth balls or gel blocks is the difficulty in determining the proper quantity of agent required to divert the treatment. Ball sealers are often ineffective because of (1) fluid communicating behind the casing between closely spaced perforations, (2) failure of the balls to seat on the perforations, and (3) abrasion of the ball sealers allowing fluid to bypass.

Limited Entry Technique

In Texas and New Mexico, this company from an improved well stimulation method called "limited entry treatment" has experienced excellent results. Based on data obtained to date, this method is much superior to the other methods of obtaining simultaneous treatment of multiple zones. The treatment is performed by (1) limiting the number of perforations in a well and (2) providing sufficient injection rates to require the restricted capacity of the perforations to divert the treatment to a greater portion of the perforated interval.

The first limited entry treatment in this region was performed in Shell TXL M-3 (TXL Tubb Field), Ector County, Texas, following a review of a paper by W. B. Murphy and A. H. Juch of Compania Shell de Venezuela (1). From December 3, 1960, to January 1, 1962, 201 limited entry treatments have been performed in a variety of reservoirs (Fig. 1). No mechanical difficulties that can be attributed to this method of treatment, have been encountered, and of the treatments performed to date, 94 per cent were successfully treated without "sandout" This percentage is considered to be a normal success ratio; and of the 13 sandouts, 6 required retreatment to obtain top allowable production. Treatments have been successfully performed in carbonate, sandstone, conglomerate, and chert reservoirs. These reservoirs range in depths from 3100 ft to 9500 ft, with bottom hole pressures varying from 1000 psi to 3600 psi.

BASIC THEORY OF FRACTURING PROCESS

General

The basic objective of all well treatments is to get the best well stimulation, compatible with cost. To get an effective treatment, it is desirable to treat as much as possible of the perforated interval. Also, the treatment should be proportioned into the perforated intervals. Both these objectives can be better fulfilled by a properly designed limited entry treatment, than by conventional

FRACTURING PROCESS

CONVENTIONAL TREATMENT

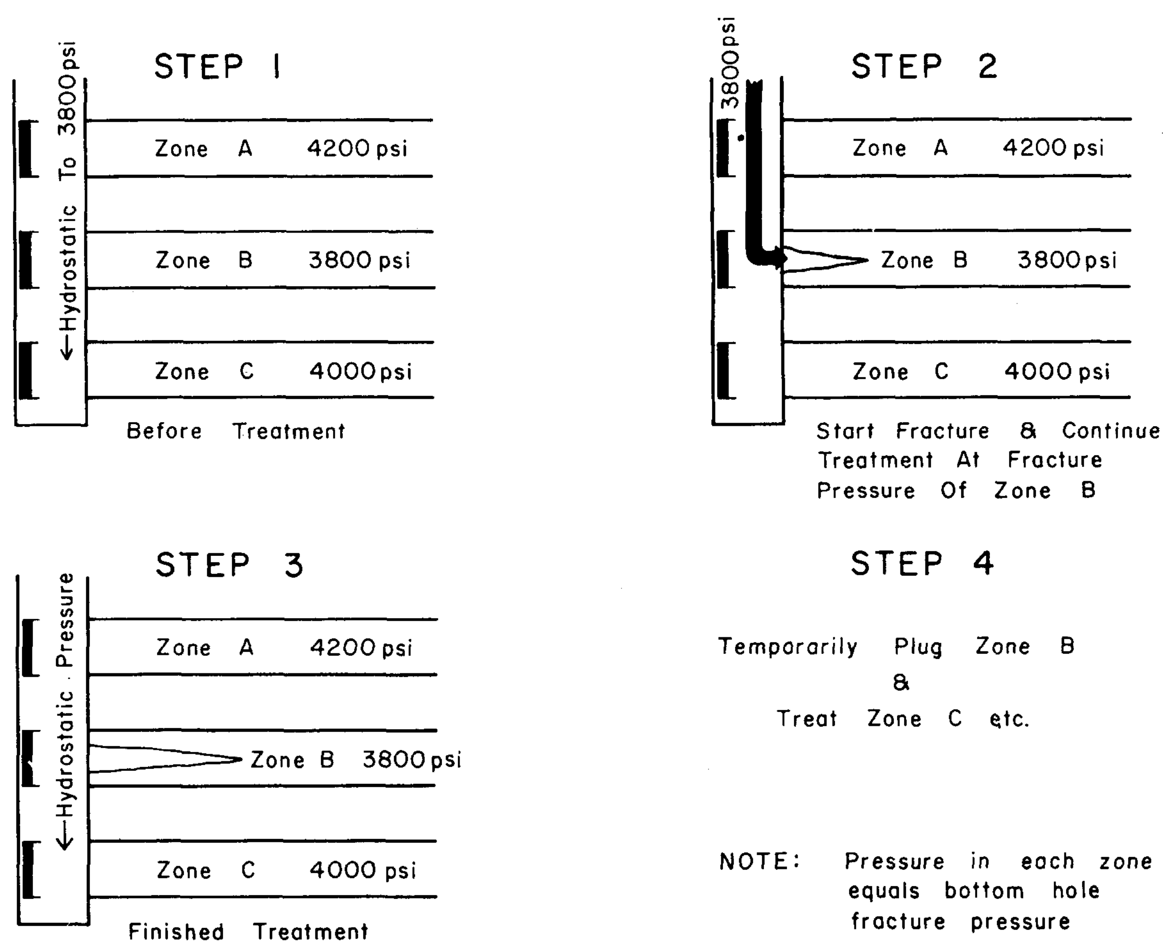


FIGURE • NO. 2

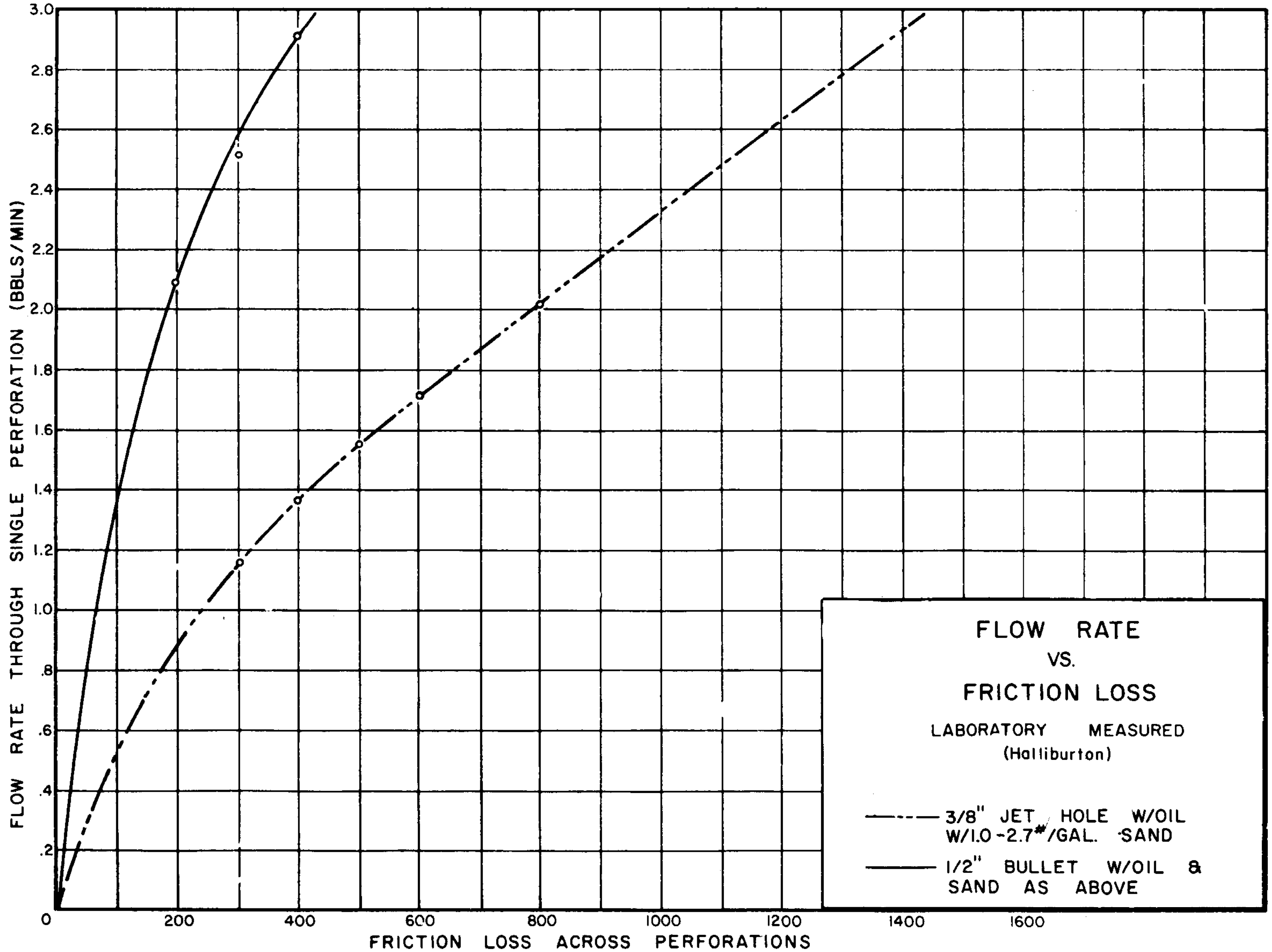

FLOW RATE THROUGH SINGLE PERFORATION (BBLS/MIN)
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
200
400
600
800
1000
1200
1400
1600
FRICTION LOSS ACROSS PERFORATIONS
FLOW RATE
VS.
FRICTION LOSS
LABORATORY MEASURED
(Halliburton)
3/8" JET HOLE W/OIL W/1.0-2.7#/GAL. SAND
1/2" BULLET W/OIL & SAND AS ABOVE

FIGURE NO. 3

treatments.

Conventional Treatment

The simultaneous treatment of multiple porous intervals by conventional methods is depicted in Figure 2. Three zones with different bottom hole fracture pressures are opened up in the same well bore. The zone which offers the least fracture resistance will take the treatment and will continue to take the treatment until a diverting method is utilized.

Limited Entry Treatment

To treat more than one porous interval, the bottom hole treating pressure must be raised above the fracture initiation pressure of each successive zone. This raise can be accomplished by limiting the number and diameter of the perforations in the casing. As seen from Figure 3, the perforation friction pressure varies directly with the rate pumped through the perforation; therefore, by increasing the injection rate, the perforation friction will be increased. In other words, the perforations are acting as individual bottom hole chokes; and as the injection rate is increased, they create an increase in available bottom hole casing pressure. The accompanying increase in pressure in the casing will then break down or fracture the next zone as indicated in Figure No. 4.

The process of breaking down each successive zone occurs rapidly, since maximum pressure and rates are established early in the treatment. Assuming adequate injection rate at the surface, one continues this process until either all the perforated zones are being fracture treated or the maximum permissible pressure on the casing is reached.

SPECIFIC FACTORS AFFECTING DESIGN OF LIMITED ENTRY COMPLETIONS

Total Pay Treatment

Best results are obtained by maintaining, during treatment, perforation friction at a maximum which insures treatment of all perforated intervals that will accept fluid (within the permissible casing pressure limitations). It is recognized that all the perforations could be treated at a lesser injection rate; however, this fact would not be true if the bottom hole fracture pressure of the individual porous members varies to any degree. Therefore, so all zones are treated, an injection rate that will give a maximum permissible casing pressure is necessary.

Small diameter perforations are preferred in limited entry treatments to (1) increase perforation friction and

FRACTURING PROCESS

LIMITED ENTRY TREATMENT

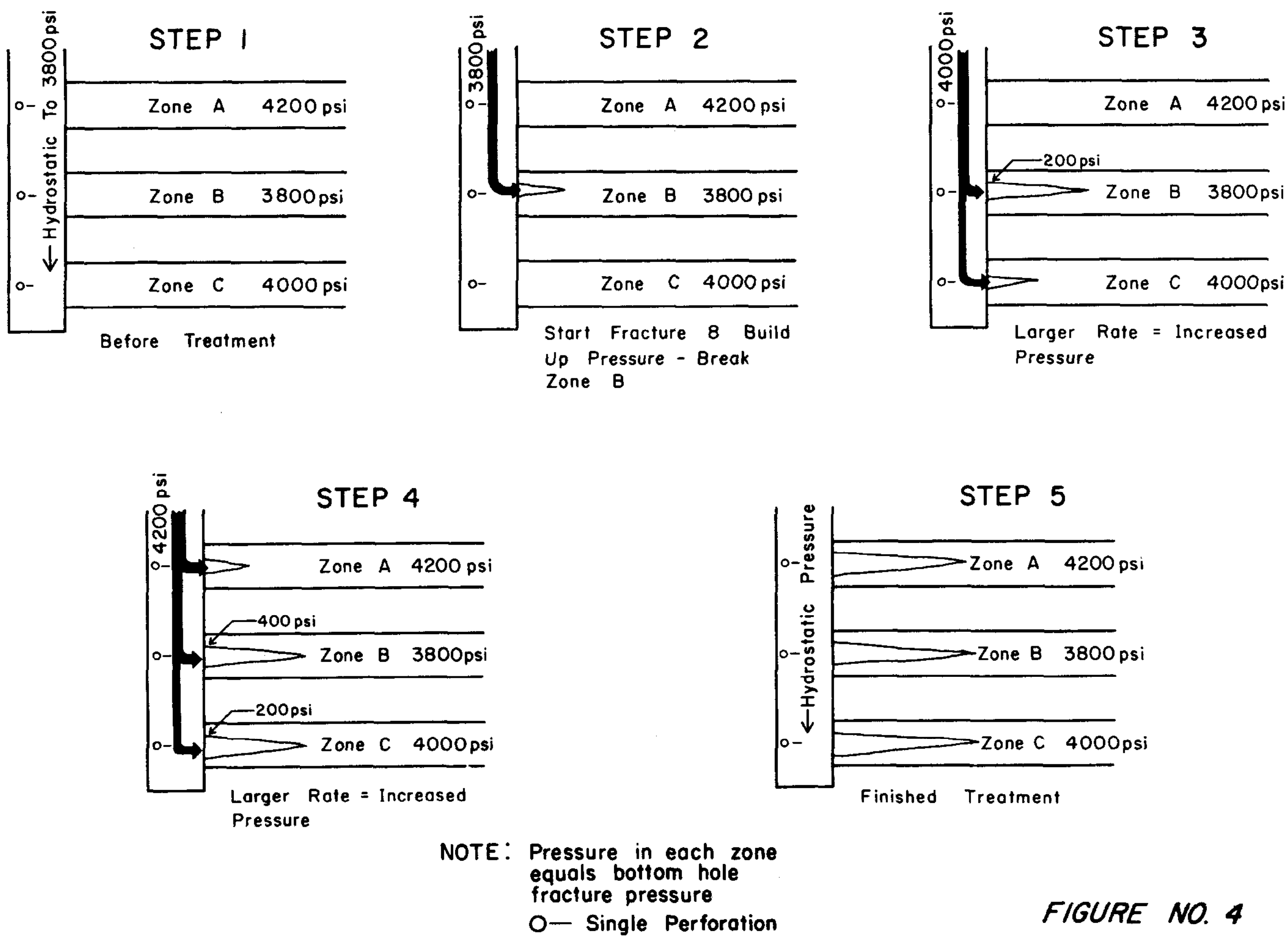


FIGURE NO. 4

(2) lower hydraulic horsepower requirements. Figure No. 3 shows that for the same perforation friction approximately twice as much fluid can be injected through a 1/2-in. hole, as through a 3/8-in. hole. Therefore, by using the smaller perforations, less hydraulic horsepower is required to deliver an injection rate adequate to maintain a maximum perforation friction. Few difficulties have been encountered to date in fracture treating through 3/8-in. jet perforations.

Halliburton has performed experiments in which a variety of treating fluids were pumped through 3/8-in. and 1/2-in. perforations. During the tests, small irregularities in the perforations were quickly smoothed out (with sand-oil mixtures) and the perforations altered from sharp-edged to round-edged orifices. The hole diameters, however, remained essentially unchanged within the normal pumping times of a fracture treatment.

Proportioning of Treatment

Limited entry treatments can be designed so the desired amount of fluids will be injected into each porous zone. This injection is an important advantage where thick zones, which require more treatment, are treated in conjunction with thin zones. It is assumed that each perforation will accept approximately the same amount of fluid; therefore, by proportioning the number of perforations according to the thickness of the zone, each zone will be given the desired amount of treatment.

A Word of Caution

The above method of proportioning fluids into zones through perforations depends on the bottom hole fracture pressures being similar; but where it is recognized that considerable variations exist in the bottom hole fracture pressures of the zones, the treatment design should be altered. The zone with the lowest bottom hole fracture pressure would normally receive the most treatment per perforation; therefore, the number and/or size of the perforations should be reduced in this zone. In the zone with the highest bottom hole fracture pressure, the converse would be true.

DESIGN OF A LIMITED ENTRY TREATMENT

As stated before, the main reason for limiting the number of perforations is to maintain control of the placement of the fracturing fluids. Therefore, it is important to know the number of perforations to use for a desired injection rate to obtain maximum perforation friction.

The equation for perforation friction is:

$$1.\quad P_{pf} = P_s = ISIP - P_f$$

where P_s = Surface injection pressure (psi)

ISIP = Instantaneous shut-in pressure (psi)

P_f = Casing or tubing friction loss (psi)

This equation was derived by substitution in the following equations:

$$2.\quad BHFP = P_s + P_h - P_f - P_{pf}$$

$$3.\quad BHFP = ISIP + P_h$$

where BHFP = Bottom hole fracture pressure (psi)

P_h = Hydrostatic pressure (psi)

As an aid to the design and analysis of a limited entry treatment, Figure No 5 has been prepared. Perforation friction pressure from Figure No 3 and average treating conditions were assumed The bottom hole fracture pressure used is .65 psi/ft, a figure which has been obtained by averaging the bottom hole fracture pressures of various formations in the Permian Basin. Few horizons deviated materially from this average figure. These assumptions have been made so that the number of holes accepting treatment can be determined by the observed surface treating pressures.

Figure No. 6 shows a comparison between the design of a limited entry completion versus a conventional completion. This well has 5-1/2-in. casing cemented through multiple porous zones. In the limited entry design ten holes were distributed into the various porous members to treat all of the pay and to properly proportion the treatment. Using Figure No. 5 with 3600 psi surface treating pressure (the pressure limitation on the casing) and 3/8-in. jet perforations, the expected injection rate would be 2.85 BPM per hole. Therefore, if an injection rate of 28.5 BPM were obtained at a surface treating pressure of 3600 psi, all ten perforations should be taking treatment. In the conventional completion as shown, with two perforations per foot of pay, any one zone could accept all of the treatment unless diverting agents were successfully used.

Treatment analysis from Field Data

The limited entry technique provides field data that can be used to determine the number of intervals that were treated. And if this analysis indicates that all zones are not being treated, the completion design can be altered. In any other method it would be difficult, if not impossible, to recognize that a change in completion design is warranted.

The three essentials necessary to determine the number of perforations accepting fluid are (1) accurate injection rates, (2) accurate surface injection pressures, and (3) an instantaneous shut in pressure (ISIP) at the beginning of the job. Injection rates obtained by averaging over prolonged periods of the treatment are not generally adequate for this method, and a continuous rate recorder is considered most helpful. Based upon experience, it is necessary to use the instantaneous shut in pressure at the start of the treatment; the use is required to obtain a perforation friction pressure that will agree with the laboratory measured data.

If a perforation friction calculation is to be made while a sand-oil mixture is being injected into the formation, the instantaneous shut in pressure as measured at the surface must be corrected for the change in hydrostatic pressure due to the addition of sand. For a sample calculation of number of perforations taking treatment. See Appendix 1.

OPERATIONAL TECHNIQUES

Opening Perforations Prior to Treatment

The major difficulty that has been encountered in limited entry treatment has been insuring that all holes are open prior to the fracture treatment. Seldom are all of the perforations able to accept fluids without being acidized. It is believed that this problem exists with conventional completions, but usually remains unnoticed; however, where the number of perforations are greatly limited, it becomes obvious if any are not open to the formation.

An acidizing technique has been adopted, but the technique is only practical for limited entry completions.

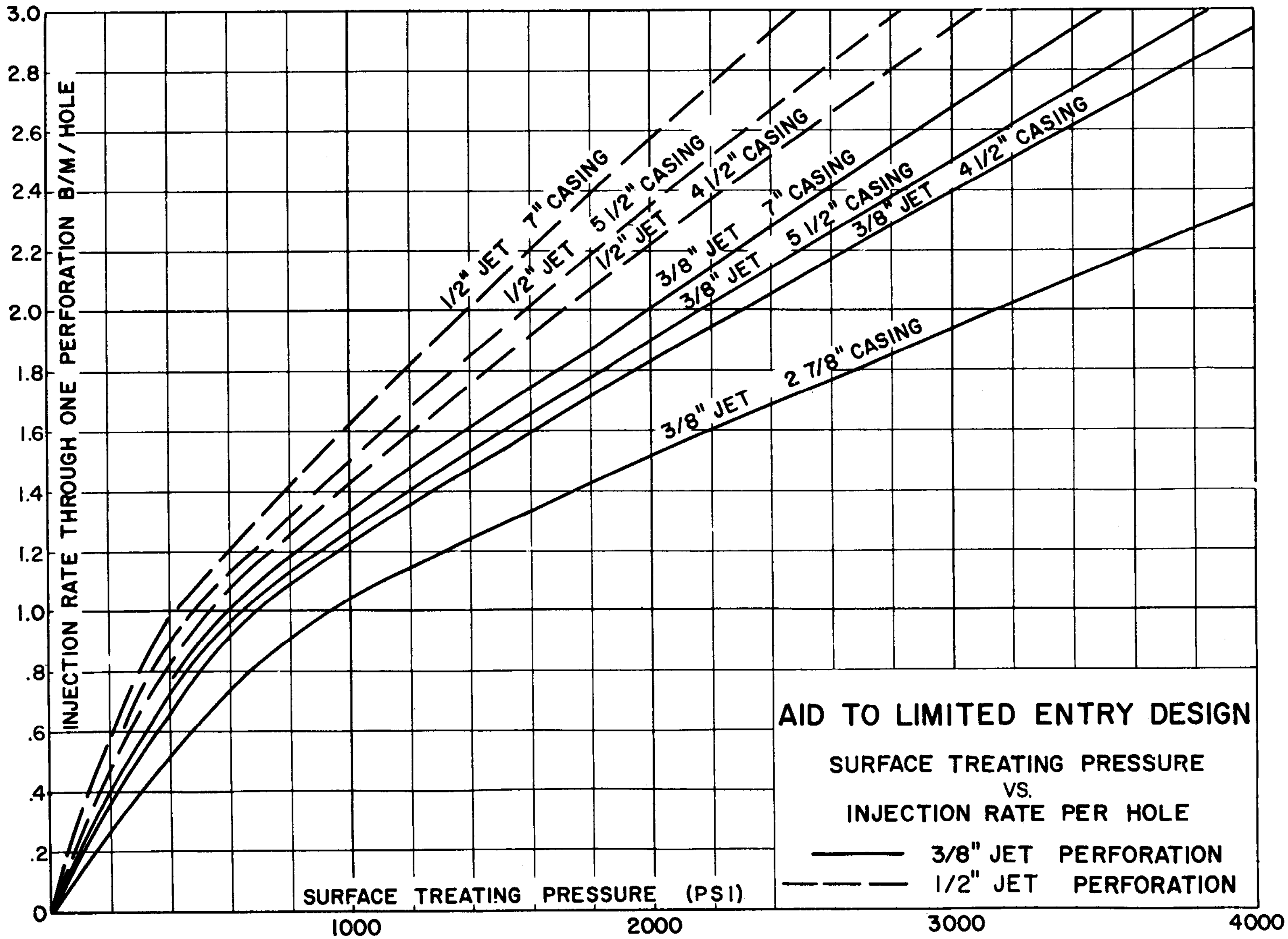

AID TO LIMITED ENTRY DESIGN
SURFACE TREATING PRESSURE
VS.
INJECTION RATE PER HOLE
3/8" JET PERFORATION
1/2" JET PERFORATION
INJECTION RATE THROUGH ONE PERFORATION B/M/HOLE
SURFACE TREATING PRESSURE (PSI)
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
1000
2000
3000
4000
1/2" JET 7" CASING
1/2" JET 5 1/2" CASING
1/2" JET 4 1/2" CASING
3/8" JET 7" CASING
3/8" JET 5 1/2" CASING
3/8" JET 4 1/2" CASING
3/8" JET 2 7/8" CASING

FIGURE NO. 5

COMPARISON OF COMPLETION DESIGN

LIMITED ENTRY VS. CONVENTIAL

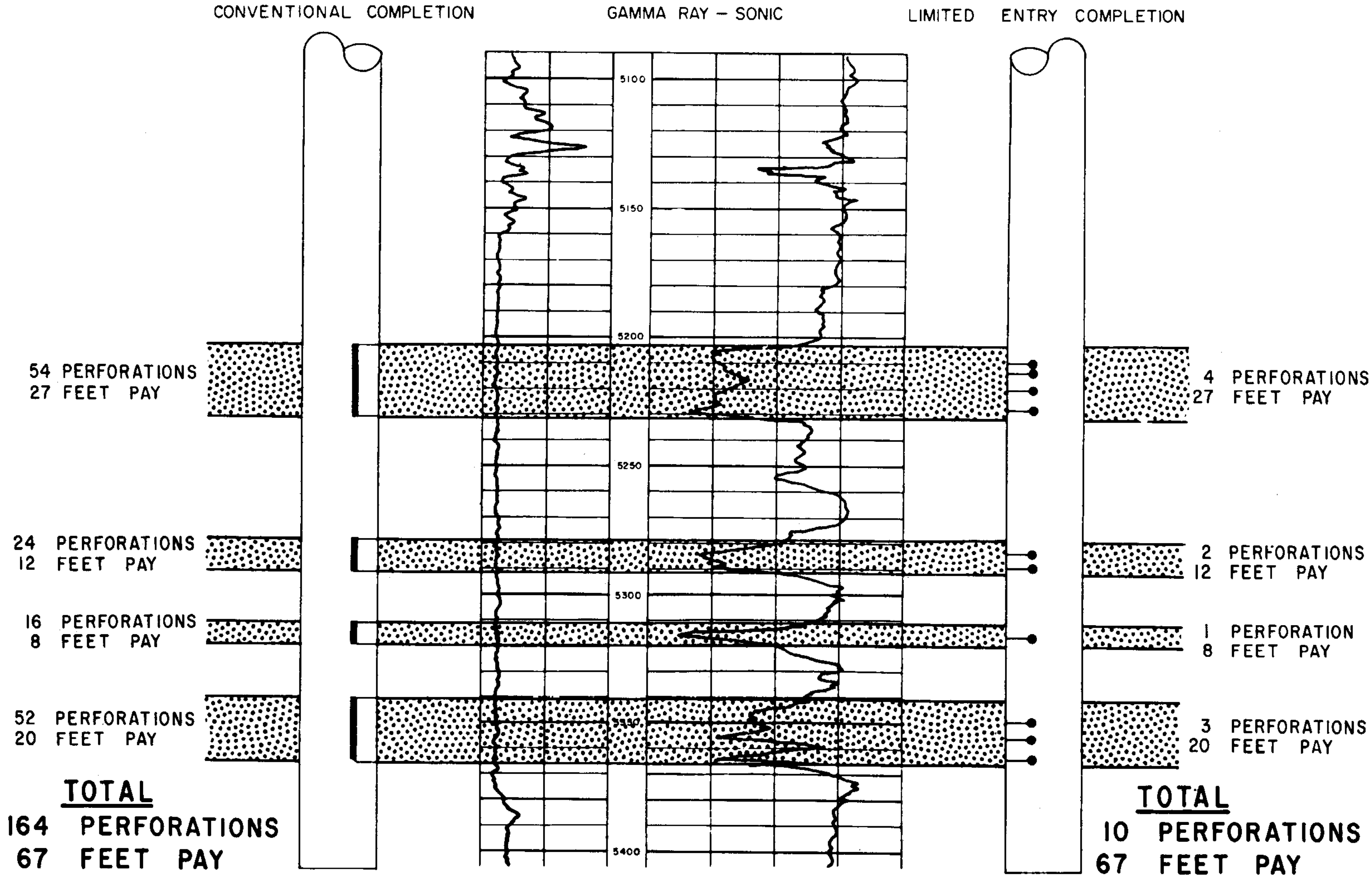


FIGURE NO. 6

TABLE NO. 1

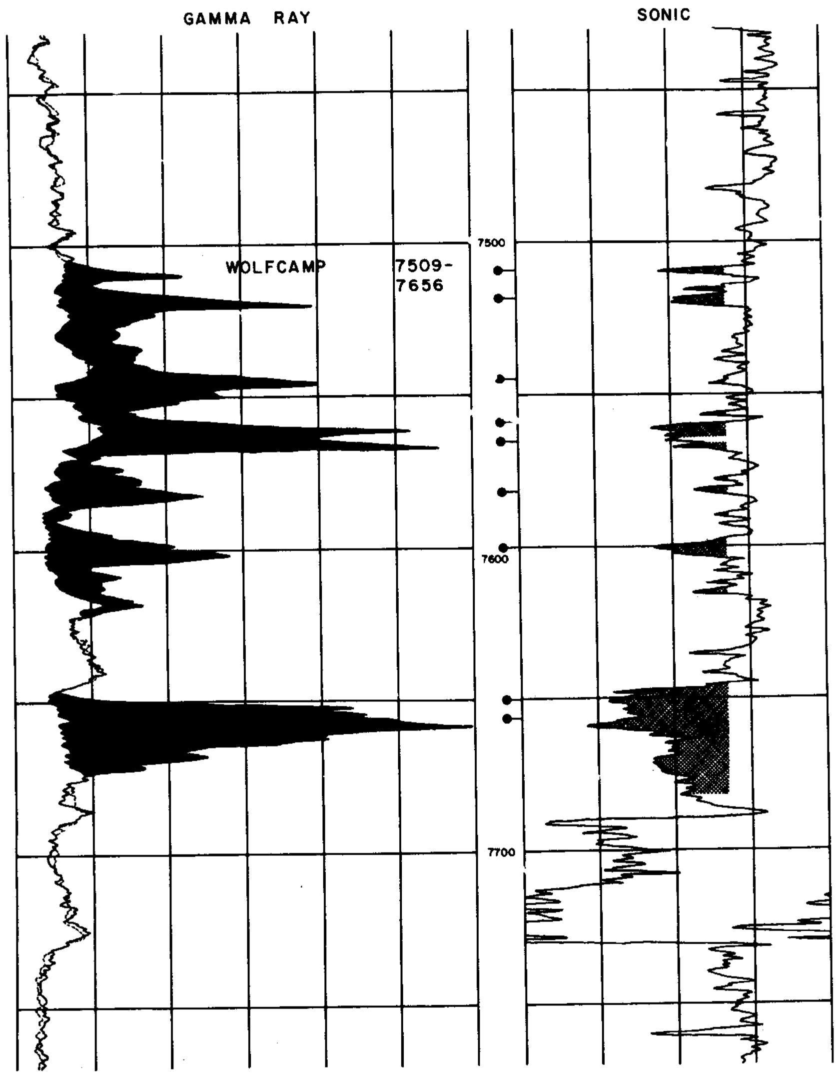
A COMPARISON OF INITIAL WELL PERFORMANCE
LIMITED ENTRY TECHNIQUE VERSUS CONVENTIONAL TREATMENT
TXL-TUBB FIELD - LOWER CLEAR FORK FORMATION
ECTOR COUNTY, TEXAS

LEASE & WELL NO.	NET PAY	NUMBER PERFORATIONS	FRACTURE TREATMENT			POTENTIAL TEST			PRODUCTIVITY INDICES DATA			
			OIL (GALS)	SAND (LBS)	BALL SEALERS	BOPD	BWPD	CHOKE	KH	K(MD)	(P.I.)	SPECIFIC P.I. X 10^3
LIMITED ENTRY TREATMENTS												
TXL M-3	58	33	30,000	45,000	18	260	23	32/64	364	6.28	.379	6.53
TXL L-19	76	24	25,000	37,500	7	235			MECHANICAL FAILURE ON BUILDUP TEST			
TXL L-23	48	21	25,000	37,500	-	155	-	16/64	81	1.69	.086	1.79
TXL L-24	47	20	30,000	45,000	4	292	-	20/64	154	3.51	.601	12.79
TXL E-6	43	20	30,000	45,000	7	276	-	16/64	407	9.47	.338	7.86
AVERAGE	54	24	28,000	42,000	7	244			254	5.24	.351	7.24
CONVENTIONAL TREATMENTS												
SLATOR B-5	36	160	30,000	42,500	110	193	-	30/64	31	0.86	.050	1.39
SLATOR C-3	35	202	25,000	50,000	120	180	-	16/64	33	0.94	.050	1.43
SLATOR C-4	74	312	30,000	45,000	120	172	-	24/64	68	0.92	.121	1.64
TXL K-16	45	134	25,000	37,500	100	197	4	24/64	62	1.38	.196	4.36
THOMAS A-3	46	348	15,000	22,500	200	233	-	20/64	20	0.43	.028	0.61
THOMAS F-7	52	316	30,000	60,000	160	226	12	16/64	15	0.29	.023	0.44
THOMAS 6	60	250	25,000	50,000	180	254	-	16/64	55	0.92	.132	2.20
TXL L-21	55	142	30,000	60,000	80	246	20	20/64	41	0.75	.059	1.07
AVERAGE	50	233	26,250	46,000	138	213			41	0.81	.082	1.64

KH = PERMEABILITY (MILLIDARCIES) × FEET OF PAY

PI = PRODUCTIVITY INDEX = BARRELS (PER DAY) PER PSI PRESSURE DROP

$$\text{SPECIFIC PI} = \frac{\text{PRODUCTIVITY INDEX}}{\text{NET FEET PAY}}$$



MORE EFFECTIVE PAY TREATMENT
BY
LIMITED ENTRY DESIGN

SHELL- *TXL* K-18

TXL WOLFCAMP FIELD

ECTOR CO., TEXAS

LEGEND

- - - - - GAMMA RAY LOG BEFORE TREATMENT

——— GAMMA RAY LOG AFTER TREATMENT

●— SINGLE PERFORATION

▓ NET PAY

FIGURE NO. 7

The procedure involves staging the acid in small slugs separated by a maximum of two ball sealers in an oil spacer. The number of stages is determined by the number of ball sealers required to "ball out" the perforations. This "ball out" allows a better estimate of the number of perforations that are open at the end of the acid treatment. After "ball out" occurs, pressure is held on the remaining acid in the casing and provides every opportunity for additional perforations to be opened.

Fracture Treatment

Limited entry fracture treatments have been performed with injection pressures, rates, treating fluid types and volumes similar to those of conventional treatments. But sometimes, it is not desired or possible to have injection rates sufficient to insure treatment of all the perforations; and in this case ball sealers can be effectively used as a diverting agent. Experience indicates ball sealer action to be 100 per cent effective in limited entry treatments, and this effectiveness may be because of higher injection rate per hole and greater separation between perforations. However, extra precaution should be taken to avoid excessive pressure surges because of the excellent ball sealer action.

Individual perforations sometimes sandout during treatment, and a decrease in injection rate is indicative of the time and number of perforations affected when sandout occurs. A continuous rate recorder is necessary for observing the loss of perforations taking treatment, and it is most helpful in determining the proper number of ball sealers to drop during the job.

A COMPARISON OF LIMITED ENTRY VERSUS CONVENTIONAL COMPLETIONS

The following data from wells in the TXL-Tubb Field (Lower Clearfork formation) are offered as a comparison of initial performance of similar wells in an area where the comparison is available. The wells are comparable in the feet of pay developed, the size of fracture treatments, and the expected ultimate recoveries.

The following table is a tabulation of all Shell TXL-Tubb wells in which pressure build-up tests have been taken. The data are considered to be of good quality because of the exceptionally good pressure buildup curves.

As indicated on Table No. 1 the initial measurement of average Kh for conventional vs limited entry treated wells has been increased from 41 to 254 millidarcy-ft or an increase of 6.2 times. Productivity index as calculated from pressure build-up data, has been increased an average of 4.3 times over that of conventionally treated wells. Specific productivity index (P.I. per net ft pay) has been increased an average of 4.4 times. The average official potential test (OPT) has been 31 BOPD higher for the limited entry completions.

FIELD EXAMPLES OF LIMITED ENTRY TREATMENTS

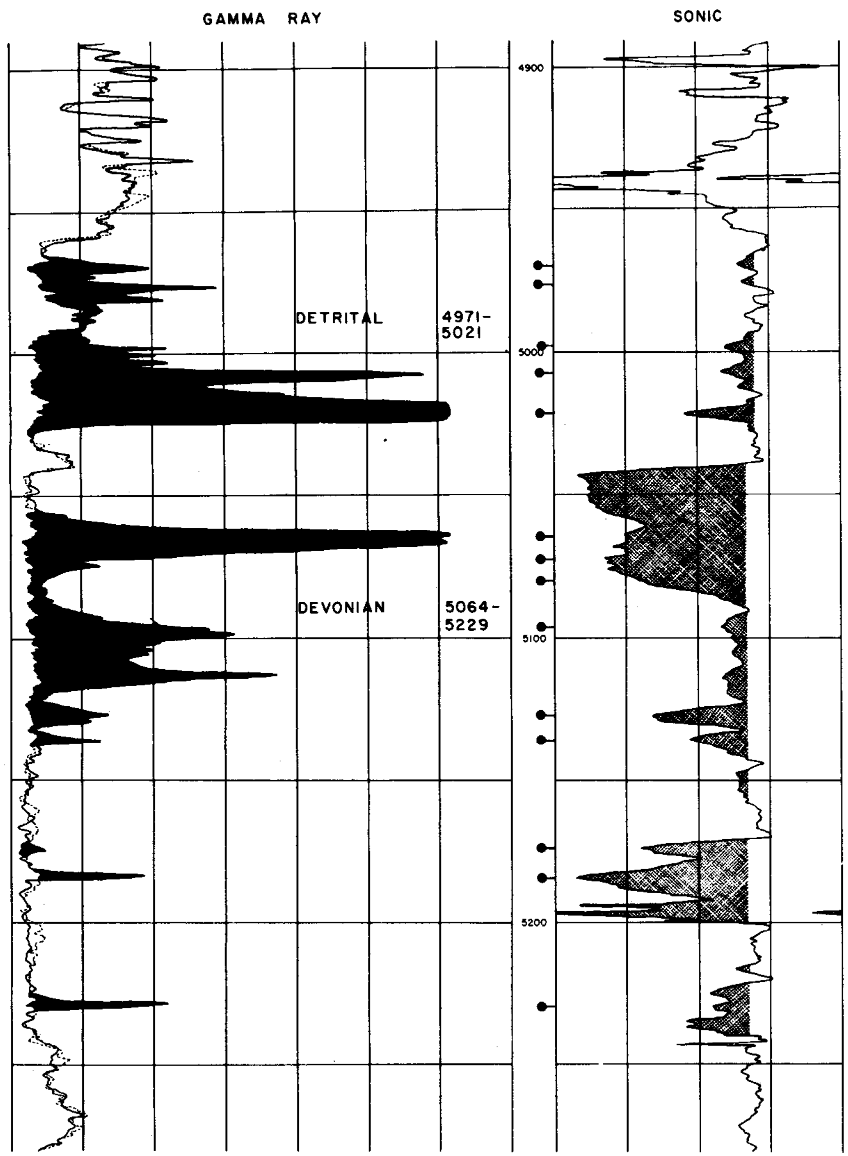
Figure 7 shows the design and fracture treatment results of the Wolfcamp formation in TXL-K-18 Ector County, Texas. For a sample calculation of the design and analysis of results from this well, see Appendix No. 1. TXL-K-18 was fracture treated with a radioactive sand; therefore, any radioactive increase above that of the base gamma ray log is considered to be an indication of the fracture treated intervals. The nine perforations used were proportioned throughout the pay, and it should be noted that the perforations were placed so all the pay was fracture treated even though it was not perforated. The well was potentialed flowing 254 BOPD, through an 18/64-in. top choke, with a flowing tubing pressure of 300 psi.

The simultaneous fracture treatment of two separate horizons, the El Cinco Detrital and El Cinco Devonian Fields, is shown in Figure 8. Both horizons were fracture treated with radioactive sand in a single operation, and the radioactive tracer log indicates that the porosity was successfully fracture treated except for the bottom three Devonian perforations. This example is of a problem in design, pointed out by a review of the treatment analysis and the tracer log. Based upon the porosity log, it appears that the design should have been straight forward, but to account for the failure to treat the lower Devonian interval there are two possibilities: (1) larger jet perforations than anticipated, resulting in the upper perforations taking most of the treatment and (2) the bottom hole fracture pressure of one zone being much larger than that of the other. Information has since become available that indicates the Devonian bottom hole fracture pressure to be about 600 psi greater than that of the Detrital. This difference would allow the Detrital perforations to accept more of the treatment than was originally anticipated (see derivation of Equation No. 1 in Appendix). Both of these problems can be solved by recognizing that they exist and by varying the design of the treatment. The well was completed as a dual producer flowing 392 and 538 BOPD from the El Cinco Detrital and Devonian Zones respectively. However, even though the performance of this well is good, the information obtained indicates that future remedial operations can be justified. And with the combination of the limited entry designed completion and the radioactive tracer log, future remedial operations are greatly simplified.

With limited entry treatment, close proximity of two formations is not necessarily required for a successful simultaneous treatment. An example of this is shown in Figure 9. The Tubb (LCF) and the Devonian horizons, separated by about 1350 ft, were successfully fracture treated in one operation in the TXL L-26, TXL Fields, Ector County, Texas. The Tubb (LCF) and Devonian zones were potentialed flowing 132 and 435 BOPD respectively.

CONCLUSIONS

1. Limited entry treatments have proven to be more effective than are other methods in diverting treating fluids to multiple horizons. There have occurred no mechanical failures that can be attributed to this technique.
2. Performance to date of limited entry completions is superior to that of conventionally treated wells.
3. The number of perforations accepting fluid at any time during a treatment can be determined by calculations made from field observations. To estimate the proportion of the treatment received by the various perforations, a continuous injection rate recorder is desirable.
4. Gamma ray tracer surveys of radioactive sand used during fracture treatments have provided a graphical record of (1) the effectiveness of the limited entry technique in diverting the treatment and (2) the amount of the porous interval treated through one perforation.
5. The simultaneous treatment of dual horizons offers great potential savings of completion costs.
6. The limited entry technique is not devoid of problems: sometimes portions of the pay remain untreated. However, by the use of the information gathered during the treatment, this problem can be recognized and improvements in the design can be



SIMULTANEOUS TREATMENT OF SEPARATE HORIZONS

BY

LIMITED ENTRY TREATMENT

SHELL-*WOOD-COWDEN 1*

EL CINCO DETRITAL & EL CINCO DEVONIAN FIELDS

CROCKETT CO., TEXAS

LEGEND

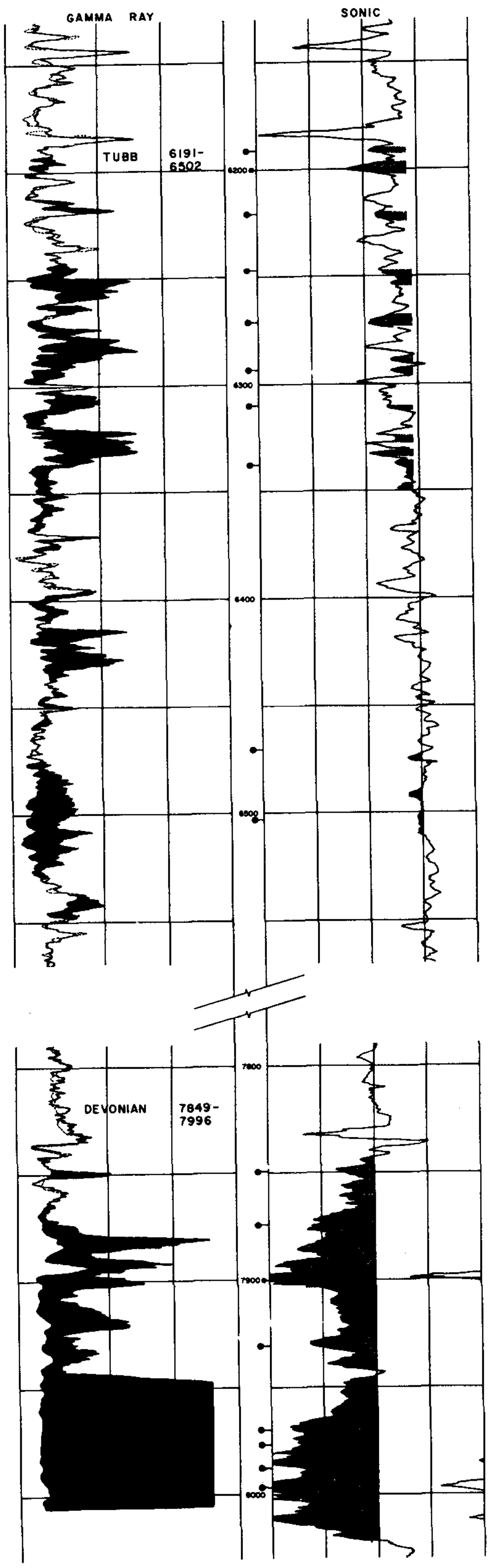
- - - - - GAMMA RAY LOG BEFORE TREATMENT

——— GAMMA RAY LOG AFTER TREATMENT

●——— SINGLE PERFORATIONS

▭ NET PAY

FIGURE NO. 8



SIMULTANEOUS TREATMENT OF SEPARATE HORIZONS

BY

LIMITED ENTRY TREATMENT

SHELL - *TXL* L-26

TXL TUBB (LCF) &
TXL DEVONIAN FIELDS

ECTOR CO., TEXAS

LEGEND

- GAMMA RAY LOG BEFORE TREATMENT
- GAMMA RAY LOG AFTER TREATMENT
- SINGLE PERFORATION
- NET PAY

FIGURE NO. 9

made. In any method other than the limited entry technique, it would be difficult, if not impossible, to recognize that pay intervals are being left untreated.

APPENDIX NUMBER ONE

SAMPLE CALCULATION OF DESIGN AND ANALYSIS OF A LIMITED ENTRY TREATMENT

DATA:

Well Number: TXL K-18, TXL-Wolfcamp Field, Ector County, Texas
Casing: 7-in. 23 lb
Gross pay interval: 7509-7682 ft
Net pay: 63 ft

Sample Calculation of Design

This well is to be fracture treated down 7-in. casing with a maximum permissible casing pressure of 3600 psi. From Figure 5 a surface treating pressure of 3600 psi gives an injection rate per perforation of 3.1 BPM for a 3/8-in. hole - 7-in. casing. Based upon the pay distribution as shown by the porosity log (Fig. 7), a total of nine holes was chosen to effectively proportion the treatment over the pay interval. Therefore, the expected injection rate would be: 3.1 BPM perforation X 9 perforations = 28 BPM at 3600 psi. The calculated injection rate was acceptable. If this injection rate had been undesirable, the number and placement of the perforations would have been reviewed.

Sample Calculation of Treatment Analysis

DATA:

Perforations: Top 7509, Bottom 7656, Avg. depth 7550, Holes 9.
Breakdown fluid: Oil, 36 API Gravity = .365 psi/ft
Frac fluid: Oil + 1-1/2 lb/gal sand = .415 psi/ft
Surface treating pressure (P_s) = 3600 psi
Injection rate = 31 BPM
Instantaneous shut-in pressure, surface, (ISIP) = 1700 psi
Casing Friction (P_f) at 31 B/M at 7550 depth = 315 psi

This well was fracture treated down 7-in. casing through nine 3/8-in. perforations. Instantaneous shut-in pressure of 1700 psi was measured during breakdown of formation with lease crude. The following calculation was made from data obtained while fracture treating with lease crude and sand. Therefore, it is necessary to correct ISIP for increase in hydrostatic pressure due to addition of sand as follows:

ISIP Surface - (frac fluid psi/ft - breakdown fluid psi/ft) X average depth

ISIP (Corrected) = 1700 psi - (.415 - .365) X 7550 = 1320 psi

Equation No. 1 $P_{pf} = P_s - ISIP - P_f$

Perforation friction (P_{pf}) = 3600 - 1320 315

(P_{pf}) = 1965 psi

From Figure 3 the injection rate per perforation BPM at a perforation friction of 1965 psi is 3.6 BPM per perforation. Therefore, the theoretical rate through all perforations would be 9 X 3.6 = 32 BPM.

This rate compares with the observed injection rate of 31 BPM or 3.45 BPM per perforation.

From this comparison, it is concluded that all nine holes were treated. See Figure 7 for confirmation of treatment analysis.

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