



A New Development in Completion Methods— The Limited Entry Technique

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Abstract

Shell Oil Co., in Texas and New Mexico, has experienced excellent results from an improved well stimulation method called the limited entry technique. This method has proven much more effective than any other method in treating thick pay sections and in diverting treating fluids to multiple horizons. The limited entry treatment technique 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.

From Dec. 3, 1960, to Jan. 1, 1963, Shell Oil Co. in Texas and New Mexico has treated 363 wells by this technique. The production performance of wells treated by limited entry completions is superior to that of conventionally 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 used successfully 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.

Introduction

The efficient simultaneous treatment of multiple porous intervals in a reservoir has been a long-standing problem in well stimulation. Various methods have been used to treat multiple zones with greater or lesser degrees of effectiveness. The bridge plug and packer method is effective, but is relatively expensive. Further, the injection rates are considerably reduced, and it is sometimes mechanically hazardous. Temporary plugging agents to divert the treatment have been used with apparent success. 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 ball sealers to seat on the perforations and (3) abrasion of the ball sealers allowing fluid to by-pass. These stimulation techniques (for the

purposes of this paper) are considered to be conventional treatment methods.

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

Limited Entry Technique

Shell Oil Co., in Texas and New Mexico, has experienced excellent results from an improved well stimulation method called the limited entry technique. Based upon data obtained to date, this method is far superior to the other methods of obtaining simultaneous treatment of multiple zones or thick pay sections. The treatment is performed by (1) limiting the number of perforations in a well and (2) providing sufficient injection rate 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, Tex., following a review of a paper by Murphy and Juch of Compañía Shell de Venezuela.^{1,2} From Dec. 3, 1960, to Jan. 1, 1963, 363 limited entry treatments have been performed in many different reservoirs (see Fig. 1). No mechanical difficulties have been encountered that can be attributed to this method of treatment. Treatment failures due to "sand-outs" have not been increased by this method. Treatments have been successfully performed in carbonate, sandstone, conglomerate and chert reservoirs. These reservoirs range in depths from 3,100 to 9,500 ft, with bottom-hole pressures varying from 1,000 to 3,600 psi.

Basic Theory of Fracturing Process

Conventional Treatment

The simultaneous treatment of multiple porous intervals by conventional methods is depicted in Fig. 2. Three zones with different bottom-hole fracture pressures are

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¹References given at end of paper.

opened up in the same wellbore. The zone which offers the least fracture resistance will take the treatment. This zone will continue to take the treatment until a diverting method is successfully 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 to be treated. This can be accomplished by limiting the number and diameter of the perforations in the casing. As seen from Fig. 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. They create an increase in available bottom-hole casing pressure as the injection rate is increased. The accompanying increase in pressure in the casing will then break down or fracture the next zone as indicated in Fig. 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, this process is continued until either all of 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

Perforation Friction

Best results are obtained by maintaining perforation friction at a maximum during treatment. This 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 would not be true if the bottom-hole fracture pressure of the individual porous members varies significantly. Therefore, to have the most assurance that all zones are being 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 (2) lower hydraulic horsepower requirements. Fig. 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 small perforations, less hydraulic horsepower is re-

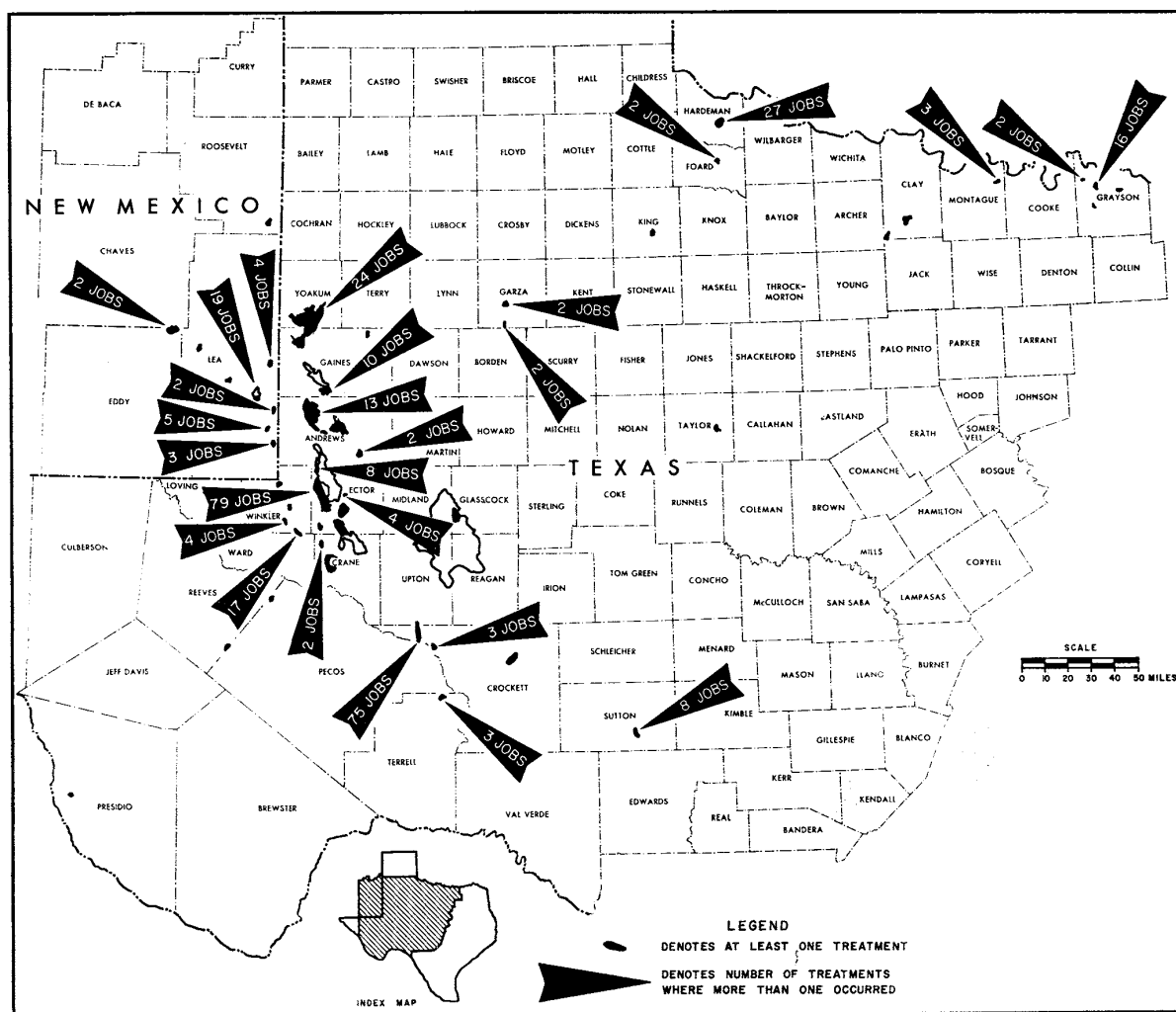


Fig. 1—Map of limited entry treatments, Shell Oil Co., Midland (Tex.) area and New Mexico.

quired 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. Therefore, 3/8-in. perforations are generally used for limited entry treatments.

Experiments have been performed by The Halliburton Co. and others where a variety of treating fluids with sand was pumped through 3/8- 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 that the desired amount of fluids will be injected into each porous zone. This 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. 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:

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

where P_s = surface injection pressure, psi,

$ISIP$ = instantaneous shut-in pressure, psi, and

P_f = casing or tubing friction loss, psi.

This equation was derived by substitution in the following equations:

$$BHFP = P_s + P_h - P_f - P_{pf}$$

$$BHFP = ISIP + P_h$$

where $BHFP$ = bottom-hole fracture pressure, psi, and

P_h = hydrostatic pressure, psi.

The design of a limited entry treatment is made by a trial-and-error method. First, a minimum number of perforations is chosen to treat all of the pay interval and properly proportion the treatment. Second, an injection rate is determined for those perforations that will maintain maximum perforation friction (within casing pressure limitations). If the calculated injection rate is considered unreasonable (either too high or too low), the number and placement of the perforations would be reviewed. For a sample design calculation, see the TXL K-18 field example.

Comparison of Conventional and Limited Entry Design

Fig. 5 shows a comparison between the design of a limited entry completion vs a conventional completion. This well has 5 1/2-in. casing cemented through multiple porous zones. In the conventional completion as shown, with two perforations/ft of pay, any one zone could accept

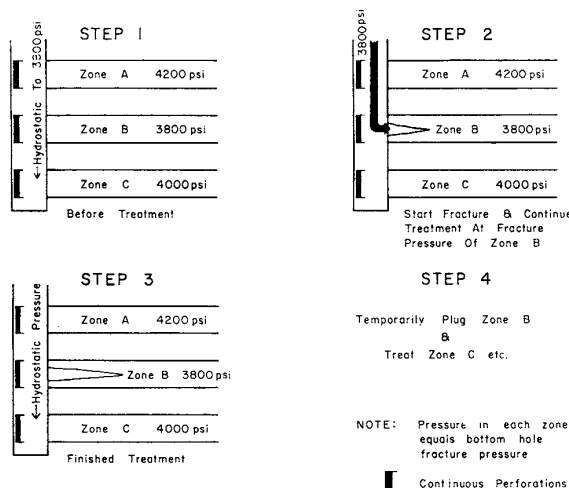


Fig. 2—Fracturing process—conventional treatment.

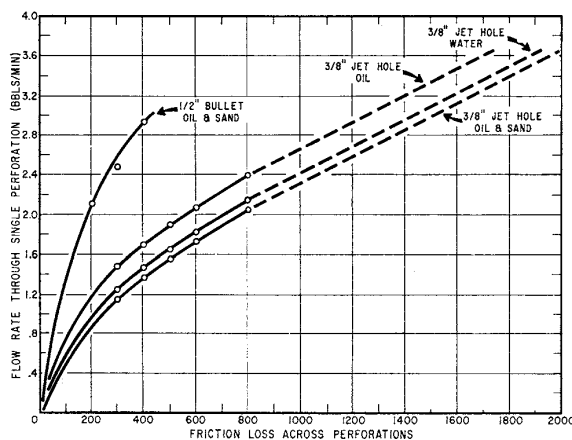


Fig. 3—Flow rate vs friction loss, laboratory measured (courtesy of The Halliburton Co.).

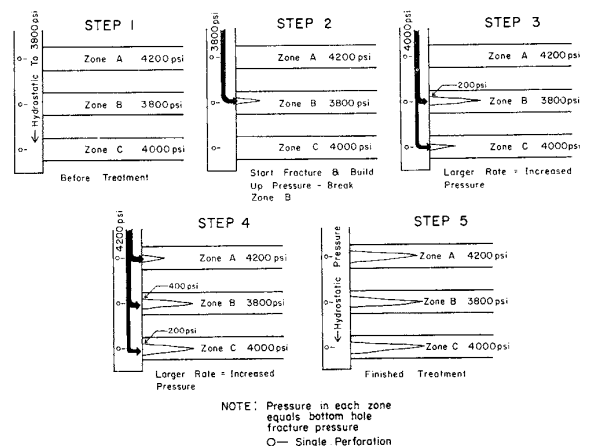


Fig. 4—Fracturing process—limited entry treatment.

all of the treatment unless diverting agents were successfully used. In the limited entry design, ten 3/8-in. holes were distributed into the various porous members to treat all of the pay and to properly proportion the treatment. The actual number of holes taking treatment can be determined from perforation friction calculations made from field data taken while treating. It would be difficult, if not impossible, to gain this kind of information while treating in the conventional manner.

Field Data Used in Treatment Analysis

The limited entry technique provides field data that can be used to determine the number of intervals that were treated. If this analysis indicates that all zones are not being treated, the completion design can be altered.

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. A continuous-rate recorder is considered most helpful.

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 (see TXL K-18 sample calculation).

Based upon experience, the instantaneous shut-in pressure should be measured at the start of the treatment. This is necessary to calculate the actual number of perforations accepting fluid during treatment. A definition of *ISIP* is: that static pressure required to hold a fracture open. Fig. 6 is a treatment pressure chart. While pumping into the formation at fracture pressure, to get an *ISIP*, pumps are stopped instantaneously. The recorded surface pressure falls abruptly to a stabilized pressure and then bleeds off slowly into the formation. The abrupt stabilized pressure point is a measurement of the *ISIP*. Note that the *ISIP* at the start of the treatment in Fig. 6 is 2,400 psi and has increased to 3,000 psi at the end of the treatment. This is not a freak occurrence. The *ISIP* increases during all treatments. Fig. 7 has been prepared to show the relationship between *ISIP* and treatment size.

The *ISIP* is plotted against the fluid volume displaced into the formation. There is a straight-line relationship between these two factors. Included in the volume displaced into the formation is the volume of fluid in front of the fracture treatment, the treatment volume itself and

any overdisplacement volume. In the example of the Hobbs K-6 (Fig. 7) the *ISIP* was 2,200 psi at the start of the treatment during breakdown with lease crude. The *ISIP* had increased to 3,500 psi at the end of the treatment after displacing 35,000 gal into the formation with lease crude. It is obvious that the calculation for perforation friction (P_{pf}) could vary considerably depending upon which *ISIP* is used. In the example of the Hobbs K-6, if the final *ISIP* were used, the calculation for P_{pf} would have had a negative value. This is an impossible figure. Using the final *ISIP* will not always give a negative value. As in the case of the Slator B-8, if the final *ISIP* were used, the P_{pf} would not be negative, but it would be some 400-psi lower than that if the initial *ISIP* had been used in the calculations. Therefore, the calculated injection rate per hole would be too low.

The only time that an instantaneous shut-in pressure is a direct surface measure of actual bottom-hole fracture pressure is at the start of a treatment. A theory is proposed to explain why this is true and why it is necessary to use the initial *ISIP* in the perforation friction (P_{pf}) calculations. Fig. 8 shows a wellbore with a perforation through which fluid is being pumped into a fracture. In this example, the bottom-hole treating pressure inside the casing is 5,700 psi and the perforation friction is 1,000 psi. The formation bottom-hole fracture pressure is 4,700 psi as measured at the start of the treatment.

Assume that the bottom-hole treating pressure and perforation friction remain constant during treatment. However, Fig. 7 shows that the *ISIP* does not remain constant. The *ISIP* is a direct surface measurement of the *BHFP*. Therefore, if the *ISIP* increases during treatment, so must the bottom-hole fracture pressure. It is proposed that the increase in *BHFP* is due to a pressure bank which is created around the fracture, due to fluid loss from the treating fluid. The fluids are forced from the fracture to

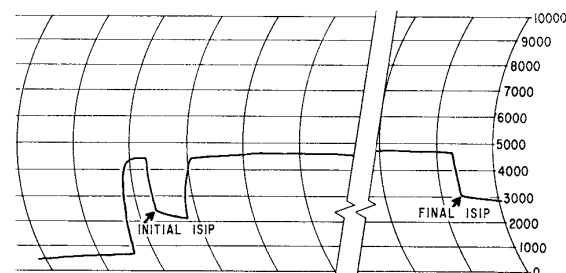


Fig. 6—Pressure chart.

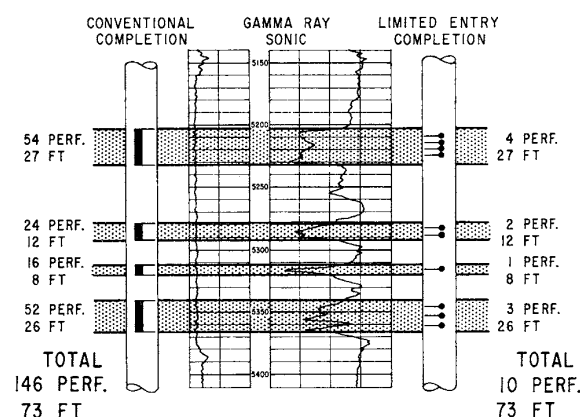


Fig. 5—Comparison of Completion design—limited entry vs conventional.

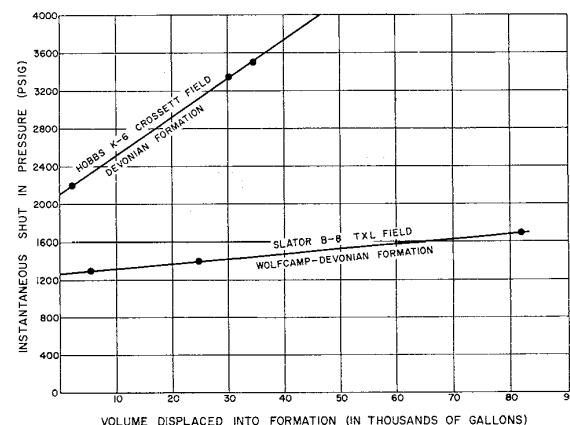


Fig. 7—Instantaneous shut-in pressure vs volume displaced into formation.

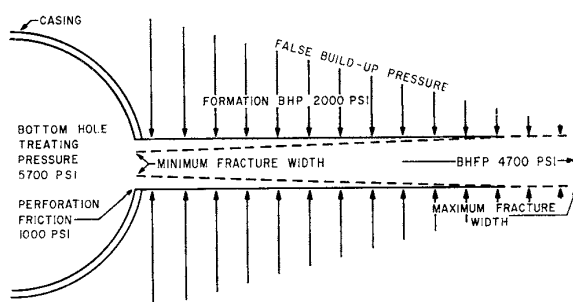


Fig. 8—Pressure bank build-up along fracture.

the matrix faster than they can escape through the matrix. This would create an increased pressure area around the fracture, or a pressure bank. As this pressure builds up, it becomes increasingly more difficult to hold the fracture open as evidenced by the increase in the *ISIP*. In other words, the pressure bank is attempting to close the fracture.

The highest pressure in the pressure bank occurs at the borehole at the mouth of the fracture. This region has had the longest time to be charged by the fluids that are forced from the fracture to the matrix. The pressure bank diminishes along the length of the fracture, and at the end of the fracture it would be essentially zero. Since there is no pressure bank build-up at the end of the fracture, the *BHFP* of 4,700 psi is still the same as measured initially when the treatment was started. Fluids can still escape along the fracture at the same *BHFP* as was initially measured at the start of the treatment. Therefore, the initial *ISIP* should be used in the P_{pf} calculations. Obviously, as the pressure in the pressure bank approaches the pressure inside the fracture, there will be a reduction in the fracture width which will eventually cause a reduction in the injection rate through each perforation. This, however, is not a normal occurrence.

Comparison of Limited Entry vs Conventional Completions

Multiple Porous Interval

The following data from wells in the TXL-Tubb field (Lower Clearfork formation) are offered as a comparison of initial performance of similar wells producing from multiple porous intervals in an area where the comparison is available (Table 1). The wells are comparable in the feet of pay developed, the size of fracture treatments and the expected ultimate recoveries. The pay is distributed over a gross interval of about 400 ft.

Table 1 includes 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 build-up curves.

As indicated, the initial measurement of average *Kh* for conventional vs limited entry treated wells has been increased from 41 to 254 md-ft, or an increase of 520 per cent. The productivity index, as calculated from pressure build-up data, has been increased an average of 330 per cent over that of conventionally treated wells. Specific productivity index (PI per net feet of pay) has been increased an average of 340 per cent. The average official potential test has been 31-BOPD higher for the limited entry completions.

Single Porous Interval

Data from wells in the Crossett field (Devonian formation) are presented as a comparison of initial perform-

ance of similar wells producing from a single porous interval (Table 2). The average potential test was increased from 208 to 237 BOPD. This increase of 29 BOPD in favor of the limited entry completions is not too significant. However, a review of the productivity index data shows that much better wells have been made by the limited entry technique. The permeability feet total (*Kh*) was increased from 121 to 307, or 154 per cent higher in the limited entry completions. The limited entry completions also have a productivity index that is 116 per cent higher than the conventionally completed wells. Since the conventional completions were generally given a slightly smaller fracture treatment, an attempt was made to correlate PI with the size of the fracture treatment. No relationship could be established. The limited entry completions have an average of 63 ft of pay vs 48 ft of pay for the conventional completions. Therefore, to eliminate the effect of more pay on the productivity index, the specific productivity index was calculated. This is the productivity index per foot of net pay. The specific PI averaged 63 per cent higher for the limited entry completions.

Figs. 9, 10 and 11 are presented to show the relationship between PI and feet of pay. In the conventional completions shown in Fig. 9, the PI does not increase with an attendant increase in the net feet of pay. As indicated, the PI is the same for 20 ft of pay as it is for 120 ft of pay.

Figs. 10 and 11 show a definite relationship between the feet of pay and the PI for the limited entry completions. For example, from Fig. 10 the PI for 20 ft of pay is about 0.20 bbl/psi decrease; the PI for 120 ft has been increased to about 2.30. The PI is better in the thicker pay intervals because the limited number of perforations proportioned the treatment over the entire pay interval. Whereas, when the entire interval was perforated by two

TABLE 1—COMPARISON OF AVERAGE INITIAL WELL PERFORMANCE, MULTIPLE POROUS INTERVALS—LIMITED ENTRY TREATMENT VS CONVENTIONAL TREATMENT, TXL-TUBB FIELD, LOWER CLEARFORK FORMATION, ECTOR COUNTY, TEX.

	Treatment Method	
	Limited Entry	Conventional
No. of Wells	5	8
Net Pay, ft	54	50
No. of Perforations	24	233
Fracture Treatment		
Oil, gal	28,000	26,250
Sand, lb	42,000	46,000
Ball Sealers	7	138
Official Potential Test		
BOPD	244	213
Choke, in.	21/64	22/64
Bottom-Hole Pressure Build-up Data**		
<i>Kh</i> , md-ft	254	41
<i>K</i> , md	5.24	0.81
<i>P</i> *PI	0.351	0.082
Specific <i>P</i> *PI $\times 10^{-3}$	7.24	1.64

***Kh* = permeability (md) $\times$ feet of pay; *P** = extrapolation of pressure build-up curve to an infinite shut-in time; PI = productivity index = barrels (per day) per psi pressure drop; and specific *P**PI = productivity index per net feet pay.

TABLE 2—COMPARISON OF AVERAGE INITIAL WELL PERFORMANCE, SINGLE PRODUCTIVE INTERVAL—LIMITED ENTRY TREATMENT VS CONVENTIONAL TREATMENT, CROSSETT FIELD, DEVONIAN FORMATION, CROCKETT COUNTY, TEX.

	Treatment Method	
	Limited Entry	Conventional
No. of Wells	38	20
Net Pay, ft	63	48
No. of Perforations	9	150
Fracture Treatment		
Oil, gal	18,600	11,400
Sand, lb	16,700	14,900
Official Potential Test		
BOPD	237	208
Choke, in.	13/64	14/64
Bottom-Hole Pressure Build-up Data**		
<i>Kh</i> , md-ft	307	121
<i>K</i> , md	4.9	2.5
<i>P</i> *PI	0.67	0.31
Specific <i>P</i> *PI $\times 10^{-3}$	10.6	6.5

***Kh* = permeability (md) $\times$ feet of pay; *P** = extrapolation of pressure build-up curve to an infinite shut-in time; PI = productivity index = barrels (per day) per psi pressure drop; and specific *P**PI = productivity index per net feet pay.

or more perforations/ft, only the easier intervals to fracture took treatment.

Note the two separate relationships established between PI and feet of pay in Figs. 10 and 11, both of which are limited entry completions. The wells in Fig. 11 grouped themselves into two parts of the field in downthrown fault blocks. The wells in Fig. 10 are located in between, in the upthrown fault block. The porosity and permeability for the Crossett field are considered to be controlled by the degree of weathering that has taken place in the siliceous limestone. Therefore, it appears reasonable to assume that the upthrown block, underlying an erosional unconformity, received more weathering and should have better porosity and permeability characteristics than that of the downthrown blocks. This could account for the better PI vs feet of pay relationship in the upthrown block.

Operational Techniques

Opening Perforations Prior to Treatment

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

An acidizing technique has been adopted that is practical only for limited entry completions. The procedure involves staging the acid in small slugs (100 to 200 gal) 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 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 for a short time interval to provide every opportunity for additional perforations, if any, 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. Sometimes, it is undesirable or impossible to have injection

rates sufficient to insure treatment of all the perforations. In this case, ball sealers can be effectively used as a diverting agent. Experience indicates ball-sealer action to be near 100 per cent effective in limited entry treatments. This may be due to higher injection rate per hole and greater separation between perforations. Extra precaution should be taken to avoid excessive pressure surges due to the excellent ball-sealer action.

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

Field Examples of Limited Entry Treatments

Fig. 12 shows the design and fracture treatment results

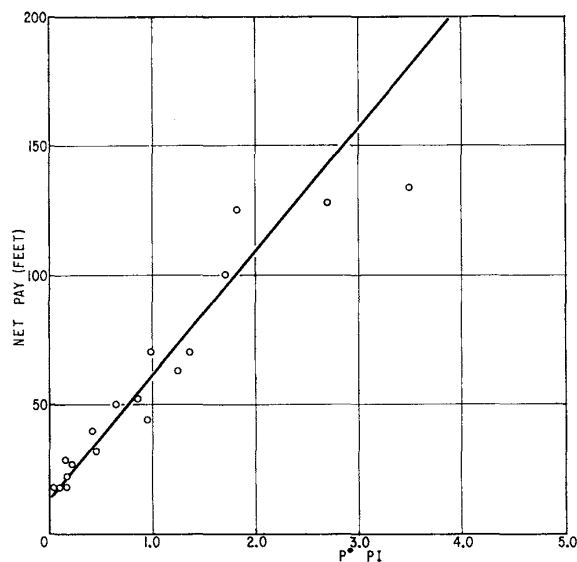


Fig. 10—Limited entry completions— P^*PI vs net pay, Crossett field, Devonian formation, Crockett County, Tex.

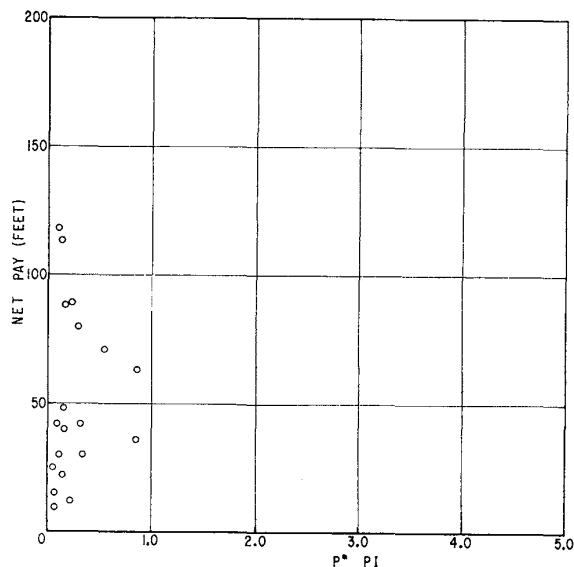


Fig. 9—Conventional completions— P^*PI vs net pay, Crossett field, Devonian formation, Crockett County, Tex.

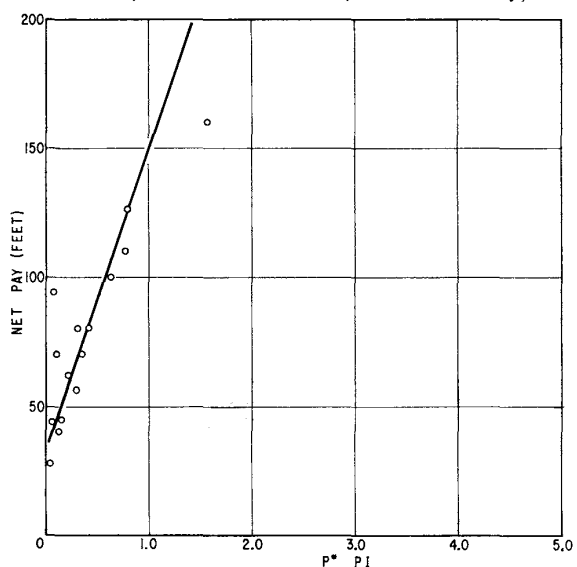


Fig. 11—Limited entry completions— P^*PI vs net pay, Crossett field, Devonian formation, Crockett County, Tex.

of the Wolfcamp formation in Shell TXL K-18, Ector County, Tex. This well was fracture treated down the casing through nine 3/8-in. perforations at 31 bbl/min. The calculations indicated that all nine holes were accepting treatment. Shell 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 interval.

Note that the perforations were placed so that all of the pay was fracture treated, as indicated by the radioactive increase opposite all of the pay, even though it was not perforated. The well was potentialized flowing 254 BOPD, through an 18/64-in. top choke, with a flowing tubing pressure of 300 psi.

Sample Calculation of Design and Analysis of a Limited Entry Treatment

Data

The following sample calculations pertain to a limited entry treatment conducted on Well No. TXL K-18 located in the TXL-Wolfcamp field, Ector County, Tex. This well was completed through 7-in., 23-lb casing with a gross pay interval ranging from 7,509 to 7,682 ft, and a net pay thickness of 63 ft.

Sample Calculation of Design

This well is to be fracture treated down 7-in. casing with a maximum permissible casing pressure of 3,600 psi. Based upon the pay distribution as shown by the porosity log (Fig. 12), a total of nine 3/8-in. holes was chosen to effectively proportion treatment over the pay interval.

From Eq. 1,

$$P_{pf} = P_s - ISIP - P_f,$$

where $P_s = 3,600$ psi (casing pressure limitation),

$ISIP = 1,700$ psi (determined from experience in formation and area), and

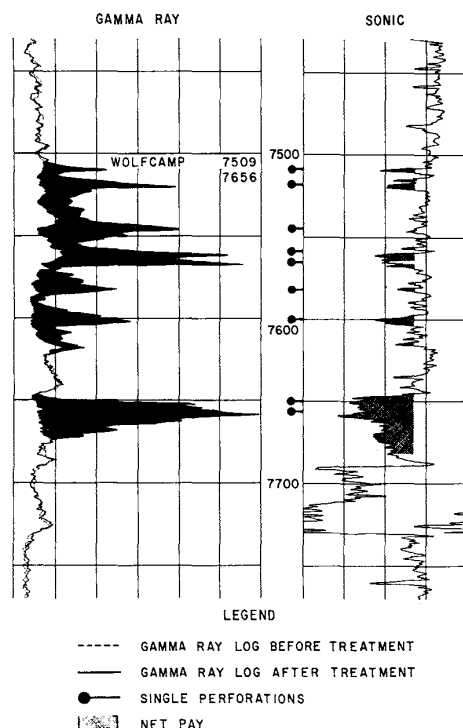


Fig. 12—More effective pay treatment by limited entry treatment, Shell-TXL K-18, TXL Wolfcamp field, Ector County, Tex.

$P_f = 190$ psi (from friction charts based upon trial rate of 25 bbl/min).

Thus,

$$P_{pf} = 3,600 - 1,700 - 190,$$

$$P_{pf} = 1,710 \text{ psi.}$$

From Fig. 3, a perforation friction of 1,710 psi for an oil and sand mixture gives an injection rate of 3.3 bbl/min/hole. From these conditions, an injection rate through nine perforations would be expected to be $9 \times 3.3 = 30$ bbl/min. Since an injection rate of 25 bbl/min was assumed to determine the casing friction pressure, calculations should be repeated assuming an injection rate between 25 to 30 bbl/min until the calculated value of total injection rate through the nine perforations equals the assumed rate. In this case it would be 29 bbl/min, or 3.2 bbl/min/hole.

The calculated injection rate was acceptable. If this injection rate had been undesirable, either too high or too low, the number and placement of the perforations would have been reviewed.

Sample Calculation of Treatment Analysis

The following data were obtained: perforations—top 7,509 ft, bottom 7,656 ft, average depth 7,550 ft, nine holes; breakdown fluid—oil, 36° API gravity = 0.365 psi/ft; frac fluid—oil + 1 1/2-lb/gal sand = 0.415 psi/ft; surface treating pressure (P_s) = 3,600 psi; injection rate = 31 bbl/min; instantaneous shut-in pressure surface ($ISIP$) = 1,700 psi; and casing friction (P_f) at 31 bbl/min at 7,550-ft depth = 315 psi.

This well was fracture treated down 7-in. casing through nine 3/8-in. perforations. Instantaneous shut-in pressure of 1,700 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) $\times$ Average Depth.

Thus,

$$ISIP \text{ (corrected)} = 1,700 \text{ psi} - (0.415 - 0.365) \times 7,550 = 1,320 \text{ psi.}$$

From Eq. 1

$$P_{pf} = P_s - ISIP - P_f,$$

Perforation Friction (P_{pf}) = 3,600 - 1,320 - 315,

$$P_{pf} = 1,965 \text{ psi.}$$

From Fig. 3, the injection rate per perforation in barrels per minute at a perforation friction of 1,965 psi is 3.6 bbl/min/perforation. Therefore, the theoretical rate through all perforations would be $9 \times 3.6 = 32$ bbl/min.

This compares favorably with the observed injection rate of 31 bbl/min, or 3.45 bbl/min/perforation.

From this comparison, it is concluded that all nine holes were treated. See Fig. 12 for confirmation of treatment analysis.

The simultaneous fracture treatment of two separate horizons, the El Cinco Detrital and El Cinco Devonian fields, is shown in Fig. 13. Both horizons were fracture treated with radioactive sand in a single operation. The radioactive tracer log indicates that the porosity was successfully fracture treated except for the bottom three Devonian perforations. This is an example 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. There are three possibilities that account for the failure to treat the lower Devonian interval: (1) larger jet per-

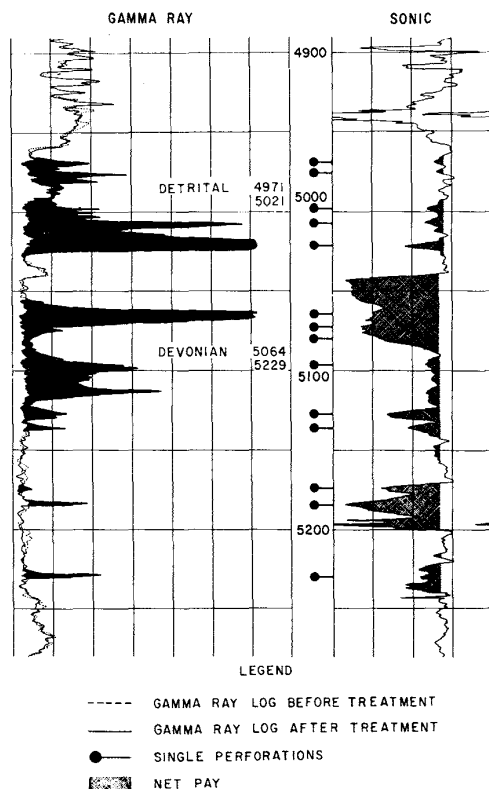


Fig. 13—Simultaneous treatment of separate horizons by limited entry treatment, Shell Wood-Cowden 1, El Cinco Detrital and El Cinco Devonian fields, Crockett County, Tex.

forations than anticipated, resulting in the upper perforations taking most of the treatment, (2) failure to provide adequate injection rate and (3) the bottom-hole fracture pressure of one zone being much larger than that of the other. All 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. Even though the performance of this well is good, the information obtained indicates that future remedial operations can be justified. 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 Fig. 14. The Tubb (LCF) and the Devonian horizons, separated by about 1,350 ft, were successfully fracture treated in one operation in the Shell TXL L-26, TXL field, Ector County, Tex. The Tubb (LCF) and Devonian zones were potentialized flowing 132 and 435 BOPD, respectively.

Conclusions

1. Limited entry treatments have proven more effective than other methods in treating multiple horizons and thick porous intervals.
2. No mechanical failures have occurred that can be attributed to this technique.
3. Performance to date of limited entry completions is superior to that of conventionally treated wells.
4. The number of perforations accepting fluid at any

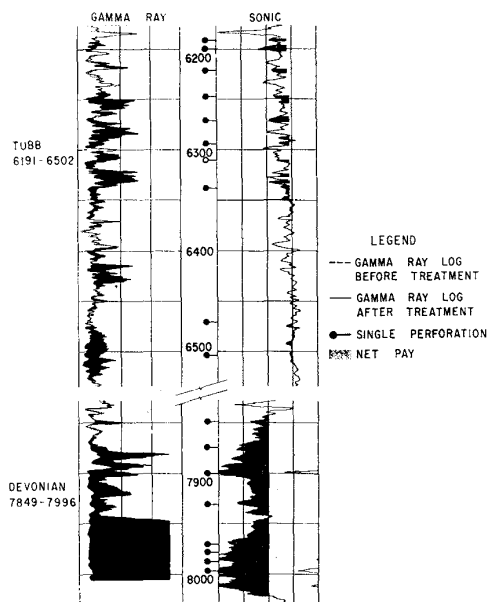


Fig. 14—Simultaneous treatment of separate horizons by limited entry treatment, Shell-TXL L-26, TXL-Tubb (LCF) and TXL Devonian fields, Ector County, Tex.

time during a treatment can be determined by calculations made from field observations. In order to estimate the proportion of the treatment received by the various perforations, a continuous injection-rate recorder is desirable.

5. 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.

6. The simultaneous treatment of dual horizons offers great savings in completion costs.

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 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.

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EDITOR'S NOTE: PICTURES AND BIOGRAPHICAL SKETCHES OF K. W. LAGRONE AND J. W. RASMUSSEN APPEAR ON PAGE 739.