WELL COMPLETIONS

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 Compañia 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 sucessfully 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.

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Exhibit 1017

The simultaneous treatment of multiple porous intervals by conventional methods is depicted in Fig. 2. Three

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Basic Theory of Fracturing Process

Conventional Treatment

The simultaneous treatment of multiple porous intervals by conventional methods is depicted in Fig. 2. Three 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.

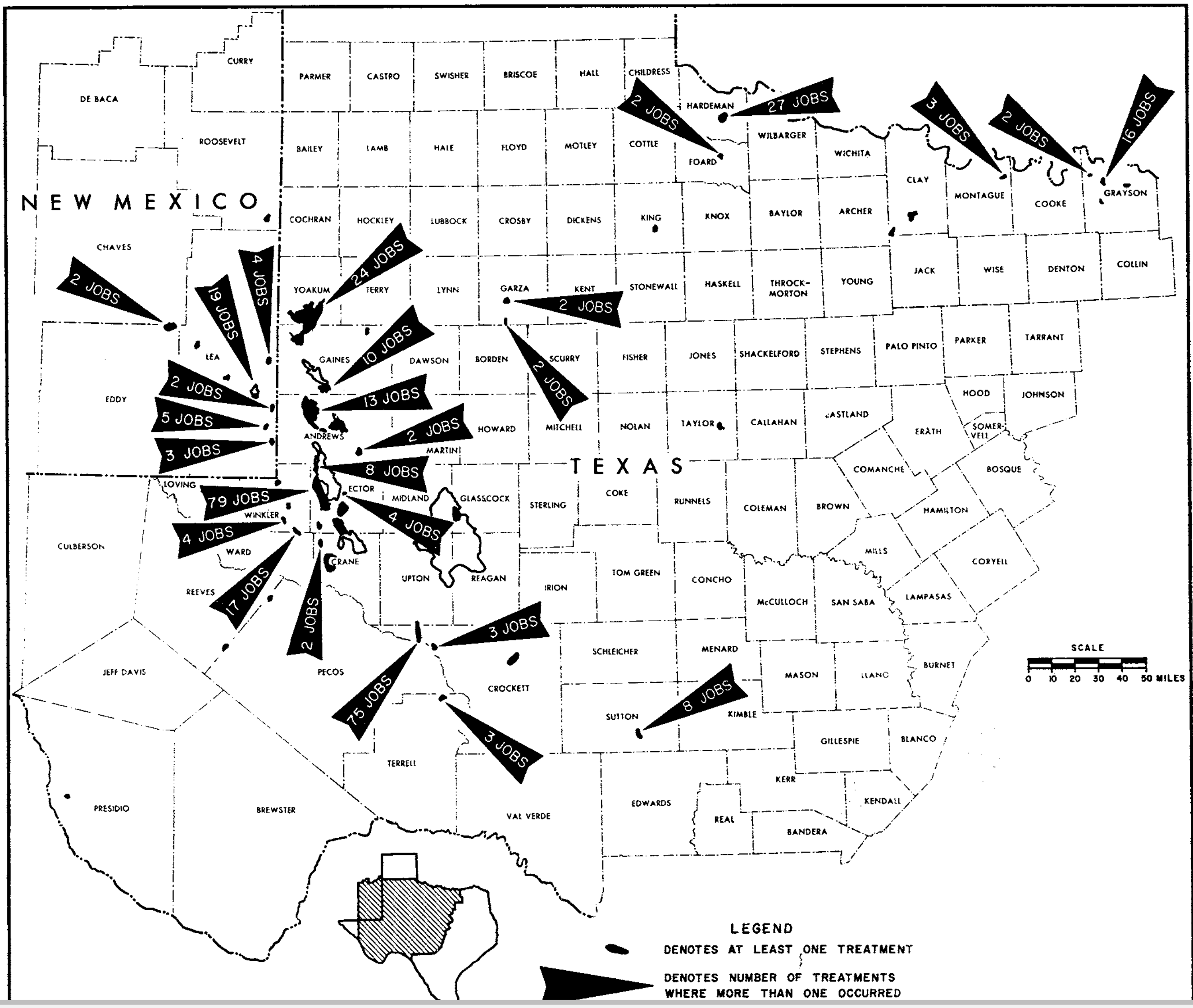
The process of breaking down each successive zone occurs rapidly, since maximum pressure and rates are established early in the treatment. Assuming adequate injection rate at the surface, this process is continued until either all of the perforated zones are being fracture treated or the maximum permissible 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 ½-in. hole as through a ⅜-in. hole. Therefore, by using the small perforations, less hydraulic horsepower is re-



quired to deliver an injection rate adequate to maintain a maximum perforation friction. Few difficulties have been encountered to date in fracture treating through ⅜-in. jet perforations. Therefore, ⅜-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 ⅜- and ½-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.

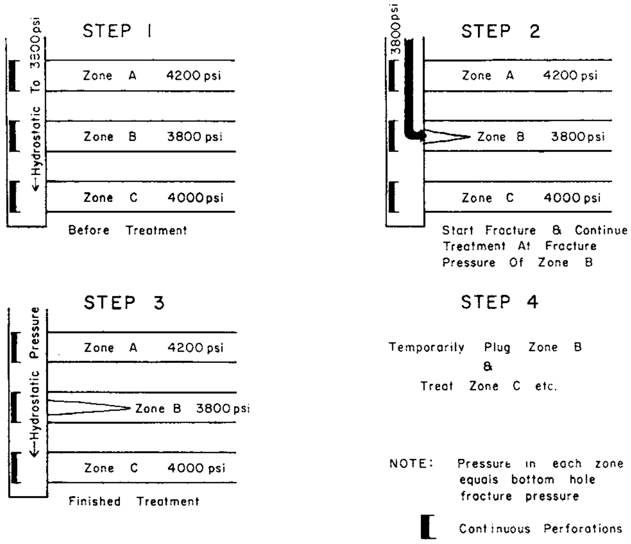
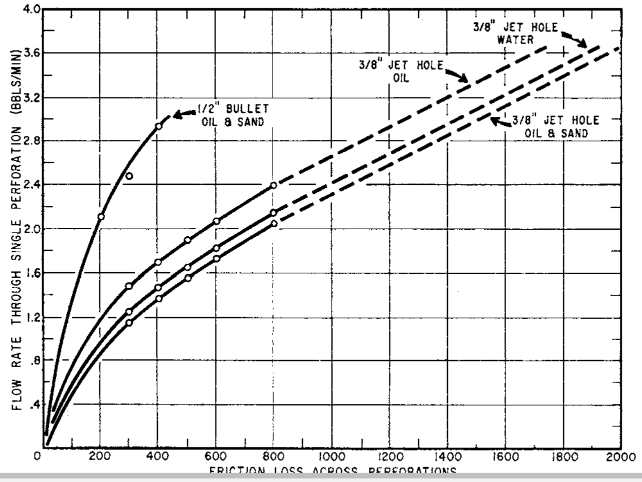


Fig. 2—Fracturing process—conventional treatment.



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:

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

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:

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

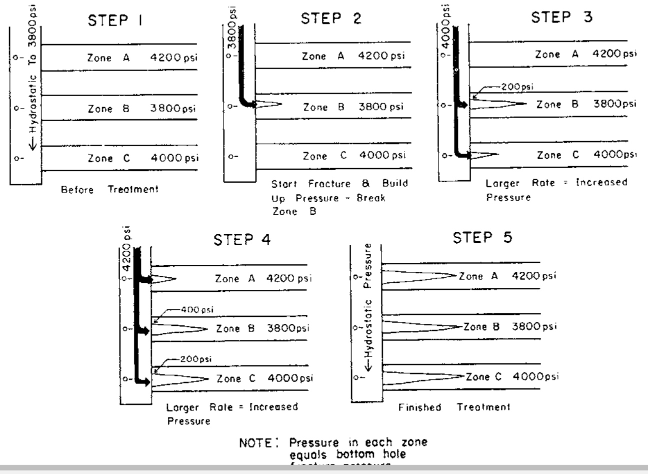
$$BHFP = ISIP + P_h$$

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 ½-in. casing cemented through multiple porous zones. In the conventional completion as shown, with two perforations/ft of pay, any one zone could accept



all of the treatment unless diverting agents were successfully used. In the limited entry design, ten ⅜-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

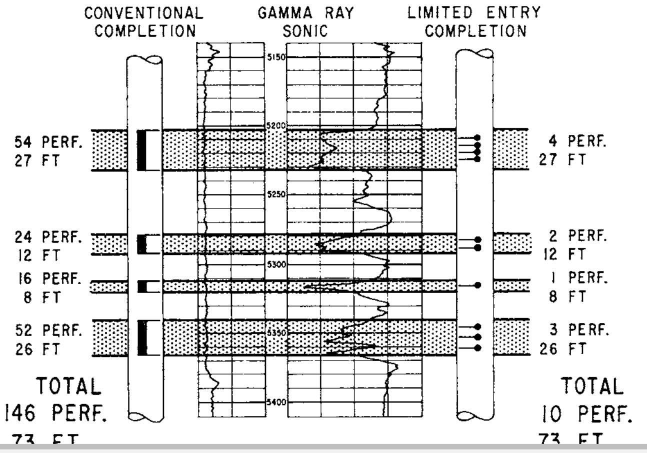
The limited entry technique provides field data that can be used to determine the number of intervals that were treated. If this analysis indicates that all zones are not being treated, the completion design can be altered.

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

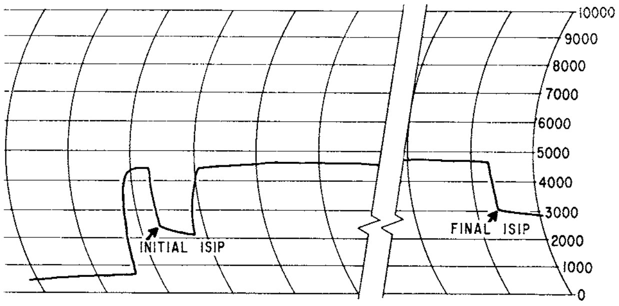
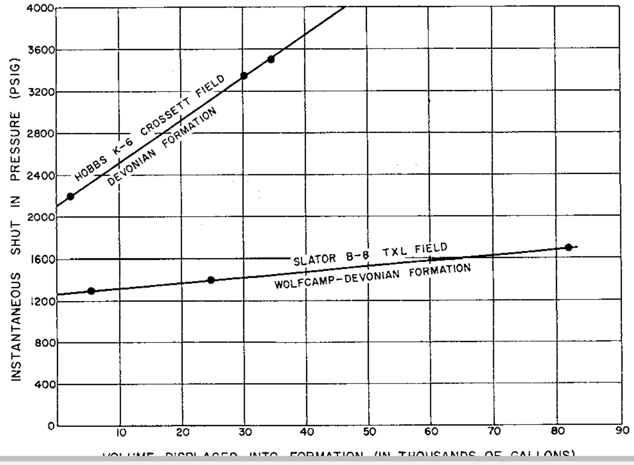


Fig. 6—Pressure chart.



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