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A CONTINUOUS MULTISTAGE FRACING TECHNIQUE

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ABSTRACT

Wells with multiple producing zones can be fractured one zone at a time during continuous pumping with a high degree of probability of treating all zones by [1] perforating with charges designed to produce round, burr-free holes; [2] perforating the same low number of holes [usually eight] into each zone; [3] perforating in acid; and [4] using sealer balls between frac stages exactly matching in number the holes in each zone.

During field trials of the process, recovered fluid-cut sealer balls indicated that quite often jet perforated holes had poor roundness and ragged burrs preventing good seal. It was necessary to have jet charges and guns redesigned to provide consistently round and burr-free entrance holes. Perforating the same number of holes per zone eliminates the guesswork when determining the number of ball sealers to use per stage. Experience has shown that perforating in acid reduces breakdown pressures, allowing the process to be used in areas where previous fracing indicated the method could not be applied. Using sufficient holes per zone to handle the total pumping rate at a low differential pressure prevents breaking down more than one zone at a time. High differential pressure from too few holes consumes energy and adds to the cost of the treatment. A calculation procedure is used to determine the holes required per zone based on flow rates and total cross sectional area of the perforations.

Radioactive frac sand and gamma ray tracer surveys have been used in conjunction with straddle packers to determine the zones treated. Success ratios calculated as the number of zones fractured divided by the number of fractures attempted have been found quite high in 7-8 zone wells and still greater in wells with fewer zones.

The method is less expensive than treating one zone at a time using isolating packers and is much surer of producing multiple fractures than simultaneously fracing generously perforated multiple zones. Continuous multistage fracturing produces maximum fracture area for a given injection rate as compared with simultaneous injection into multiple zones. The multistage technique also allows use of all the steps considered essential to good, single-stage treating.

Results of field trials have consistently indicated vertical fractures. The fracture orientation has been evidenced by low treating pressure gradients and by gamma ray tracer surveys.

Field work with radioactive propping agents provided a means of checking the quality of the cement job after fracturing. What had been

References and illustrations at end of paper.

considered a satisfactory primary cementing technique was found in many cases after fracing to give channeled cement for considerable distance above the pay section and showed poor separation or no separation between zones. The cement program in one field was modified and finally included:

1. Reciprocation during cementing of the pipe until the top plug bumped.
2. Two plugs.
3. Centralizers and scratchers across the pay.
4. Sixteen per cent gel-salt fill cement with regular heat to cover the pay section.
5. Turbulent flow of the fill cement.

With this procedure nearly all of the treatments have been confined to the pay section and the separation between zones is greatly improved. Data were determined indicating the spacing required between sets of perforations to prevent communication during fracing.

Production data are presented showing the improvement obtained with controlled frac treatments.

The general technique has also been applied to acidization of multiple zones.

INTRODUCTION

Fracturing of multizone wells becomes very expensive and even prohibitively so in some wells if each zone is separately treated with mechanical devices such as bridging plugs and packers. Separate treating of this type requires extra rental of tools, additional rig time, and repeated charges for the frac trucks.

A method commonly known as pinpoint[1] or limited entry fracturing[2] will provide positive simultaneous multizone treating, but it disadvantageously divides the injection rate among the zones being fractured, resulting in low injection rates per fracture and therefore limiting fracture extension. The method is also dependent upon high injection pressure and thus requires a large amount of pump horsepower. Other methods using various forms of gels and temporary blocking materials have been tried but they offer poor control of fracture placement.

Fracturing several zones in a well by use of ball sealers to divert the frac fluid to a new zone is unreliable as usually practiced. One reason is the difficulty in determining how many ball sealers to inject. When the well has thick and thin zones, with a corresponding variation in the number of perforations, it is impossible to determine which zone treats first so that the corresponding number of ball sealers can be injected. This process becomes more complicated as the number of zones increases. Straddle tools, flow meter surveys and radioactive tracer surveys used to check the effectiveness of this guesswork approach shows that it results in large numbers of unfractured zones.

If multistage treating with ball sealers is to reduce completion time and cost it must ensure that all zones are treated. In addition, such treating must allow sufficient flexibility to permit following the requirements of designed fluid treatments.

The generalized requisites for effective fracturing are considered to be as follows:

1. Treatment of all zones in which stimulation is desirable, using sufficient volume to give optimum economic fracture extension.
2. Correct type and concentration of propping agent to produce high capacity fractures.[3,4]
3. Effective propping agent placement requiring spearhead, propping agent fluid, and no overflush.
4. Fluid loss control[5] in spearhead and propping fluids and viscosity control in spearhead, propping fluid and flush.

In order to meet these requirements with the least horsepower it is essential that the frac fluid enter one zone at a time. This will reduce the chances of a screenout and provide the greatest depth of penetration at a given pump rate.

The purpose of the multizone fracturing method described herein is to incorporate into a continuous operation all the requirements heretofore possible only in repeated single stage frac jobs. In most cases of this type, treatment can be conducted down the casing at high injection rates without large pressure losses due to friction, but also can be applied through the tubing if necessary. The method also applies directly to multizone acid jobs. It has been repeatedly successful in the Crane, Monahans, Victoria, Oklahoma City and Hobbs areas of Gulf. Initial efforts were made at Crane by the local personnel, but most of the supporting data herein were developed at Monahans.

GENERAL METHOD

In brief, the method consists of the following:

1. Perforate in acid each zone to be stimulated, using the same small number of holes of sufficient total cross sectional area so that pressure drop at the design pump rate will be low enough [about 150 psi] to avoid simultaneous breakdown of another zone.
2. Use a perforating device which produces round, burr-free holes of known size.
3. Based on the most permeable zones, design a fluid stage consisting of spearhead, prop-

carrying fluid, and prop agent as for a single zone frac job. If an acid job, design an appropriate fluid stage for the zone.

4. Pump the first spearhead and propping fluid stage as designed, followed immediately by the number of sealer balls matching the number of holes in one zone.

5. Repeat the fourth step for each stage except that sealer balls should not follow the last stage.

6. Pump in flush fluid following the last stage. Underflush for a frac job, overflush for an acid job.

The use of some radioactive prop agent with the usual prop material has been of great aid in developing rules for spacing the fractures and in determining when cement jobs allow channeling of the frac fluids.

The full significance of the above procedure is not immediately apparent, and the following items are presented to explain the method and illustrate results.

PERFORATING

In order to assure treatment of each and every zone in a multizone attempt, perforating must be controlled in a specific manner. If it were possible to perforate each zone with one hole large enough to accept the pumping rate and then drop one ball sealer of the correct size, this would seal the hole accepting the fluid. Pumping pressure would then be increased to the value necessary to break down the next zone. This is not practical, but it is possible to perforate each zone with enough holes to permit passage of the fluid with a low pressure drop; and by matching the number of sealer balls with the number of holes in each zone, the same effect can be accomplished. The most common number of holes per zone is eight, but the number to be used is a calculated quantity as illustrated below.

1. Choose a perforation friction pressure. A small differential pressure or perforation friction is necessary to seat ball sealers; 100-200 psi is usually sufficient.

2. Determine the flow rate per perforation that will produce 100-200 psi differential. This may be calculated or taken from a curve such as Fig. 1. Next, divide the individual perforation flow rate into the total pump rate to obtain the number of holes required for each zone.

In general, the fewer the number of holes used, the less chance of leakage during fracing. This favors relatively large diameter perforations. As an example, for 25 bpm, 150 psi differential, and 0.6 in. diameter holes, 10 holes are required.

It is necessary to know the entrance hole diameter produced at the clearance the charge will be fired. Hole diameter may vary considerably with clearance.[6] The service companies usually report the hole size at 1/2 in. clearance, but they seldom provide a means of controlling or firing the jet charges at this clearance. Nearly all wells have enough deviation to cause the perforating gun to be against the casing, similar to the position shown in Fig. 2. This is an example of a 1-11/16 in. capsule gun with 90° phasing inside 7 in. OD 20 lb casing. Two of the jet streams [B and D] will strike the casing at an angle and produce elongated holes with uneven burrs which ball sealers will not seal. Clearance for one of the jets [A] is so great it may not produce a hole; the other jet [C] will produce a hole at zero clearance with less diameter than normally reported. Although this is an extreme example, it demonstrates the importance of controlling clearance and positioning the charge so that it will be fired normal to the casing. This can be accomplished by several methods. A magnetic positioning tool or a mechanical decentralizing device can be used and all the charges fired in a vertical line in the same direction. Another method is centralizing regular carrier guns. A carrier gun of near casing diameter does a fair job. But in any event, the performance curve or API RP-43 tests should be obtained from the perforating company and evaluated in terms of possible clearance variations in the well to ensure that hole diameters are approximately correct.

In addition to roundness and size requirements, perforations should be burr-free for efficient sealer ball seating. This is evident from the sketch of a typical large hole perforation shown in Fig. 3 and confirmed by recovered fluid-cut sealer balls. To date two service companies have responded with field equipment to requests for burr-free jet perforating devices meeting all the requirements. Both tools develop holes slightly larger than 0.6 in. and are decentralized carrier guns firing as many as four shots per ft in one direction. One develops a slight ridge on some holes but is quite satisfactory; the other has well rounded shoulders. Typical holes from these are also shown in Fig. 3. Sketches rather than photographs are used for clarity in reproduction.

Perforating in acid is a step that experience in both carbonate and sandstone reservoirs has proven necessary if all zones are to break down within the limiting pressure of the casing or tubing. The service companies do not object to perforating in acid if a few precautions are followed. The acid should be well inhibited and enough used to adequately cover the interval. The remainder of the hole should be loaded with a clean fluid which will wash the wireline and permit correlation for depth control above the acid. Correctly spotting acid under more dense salt water is difficult and the job is surer if the water is lightened or the acid weighted with salt or Ca Cl_2. When this is not done, perforating must be accomplished quickly before the acid lubricates out of the interval to be perforated.

It is possible to use horizontal plane perforating for the method. If the shallowest zone treats first and is blanked off by the first stage of ball sealers, all the remaining stages and sealers must pass through the restriction made by the seated balls. In small size casing it may be difficult for the balls to pass through the restriction without colliding. However, the method is feasible and is actually being used where sufficient clearance is available.

BALL SEALERS

Rubber coated nylon [RCN] ball sealers are recommended in preference to solid rubber balls. The strength of solid rubber balls is greatly decreased with small rises in temperature and the balls may fail by shear or by deforming and squeezing through the holes. This condition was experienced on a well when a few solid rubber balls were mixed with RCN balls. They were found to have deformed almost sufficient to pass through the perforations. However, rubber balls have been used successfully in low temperature wells.

Jet charges fired at the same clearance will produce entrance holes with some variation in size.[6] Some service companies plot the clearance vs. hole size curve as a band rather than a line of the average hole sizes. The band will include the maximum and minimum hole sizes expected. When choosing the size of ball sealers it is important to know the maximum size hole and to select ball sealers accordingly. Trouble is avoided if the nylon cores are slightly larger than the hole.

A valuable check on the performance of both the sealer balls and the perforating device is the inspection of sealer balls following the job. Each ball should be found to be imprinted with the perforation shape. They should show round impressions of correct diameter and give no evidence of having washed out or leaked. This check may indicate necessary changes in the perforating device or ball sealers.

Fig. 4 shows a fluid-cut sealer ball typical of many obtained from jobs using conventional perforations with burrs. While the leakage produced by a few of these will not seriously affect a job, more than a few will thief enough fluid to prevent breakdown or render ineffective treatment of the last zones. Also shown are non-fluid cut balls from burr-free holes. The balls from burr-free holes often have a ring of impregnated sand grains upon recovery, as shown on the second ball from a burr-free hole.

DEFINING ZONES

Defining a zone for fracturing purposes is usually done from logs and is a simple operation when the producing formations or zones are considerably different from the formations separating them, such as when clean sands are separated by shales. However, defining a zone is much more difficult where porous zones contain sharp variations in porosity over short intervals. In formations of this type it is necessary to estimate the height of vertical fractures in order to determine the number of entries required to treat all of the pay section. The fractures appear to extend in general to the limit of an interval of varied porosity and this then defines a zone of porosity. However, if the zone of porosity is thick, the fracture will not appear to extend across the whole zone. Entries are then spaced about 50 ft apart.

There must be sufficient dense formation between zones to prevent the fracture from extending across the dense formation and to provide a good cement seal. A "rule of thumb" used by a number of engineers for this distance is 25 ft. Low porosity intervals of five or 10 ft seldom provide sufficient separation between zones to be fractured. Fig. 5 shows communication between sets of perforations at different spacing as found after fracturing in one field. the method of determination was based on the spread of radioactive sand between sets of perforations. As an illustration, the gamma ray-neutron log from a Devonian well is shown as Fig. 6. It has four zones and would require five entries. Suggested points of entry have been marked on the log.

While there may be some objection to not perforating a porous interval immediately adjacent to another selected for perforating, experience indicates good wells are produced and radioactive tracer techniques indicate that vertical fractures pass through both intervals. In any event, the overall method described certainly produces better spaced stimulation in the well than is possible with saturation of all porosity with perforations. Saturation perforating results in holes in all desired intervals, but control of frac placement is lost and large unstimulated intervals result.

For an unfractured well to develop maximum producing ability, most of the permeable interval should be perforated. If a well is to be produced through high capacity fractures, these can be established adequately through a limited number of perforations as described above. Entry in the upper part of the reservoir should be used in water drive zones and in the lower part of the reservoir in gas cap areas. A midpoint should be used if both gas and water problems are expected.

RADIOACTIVE PROP AGENTS AND TRACER SURVEYS

Extensive use has been made of radioactive propping agents and tracer surveys. These provide information indicative of the following:

1. Whether all zones selected were treated.
2. Vertical or horizontally-oriented fractures.
3. Extent or height of vertical fractures.
4. Communication between perforations or to undesired zones.

Channeling will often differ from vertical fractures in that the increased radioactivity will only go one direction from the point of entry. A short set of perforations will usually be placed within the boundaries of a porous interval, in which case a vertical fracture would produce increased radioactivity both above and below, as shown in Fig. 7. However, when one or more sets of perforations are connected by radioactivity, the method is not capable of clearly distinguishing between channeling through the annulus or vertical fracturing. Fig. 5, therefore, can only be interpreted as indicating the communication between sets of perforations resulting possibly from the combined effects of both types of communication. Logs showing two or more sets of perforations connected can only be positively interpreted as indicating a minimum of one fracture and a possible maximum number of fractures equal to the sets of perforations connected. Straddle packer tests in a number of wells have shown that communication does exist when indicated by radioactivity.

The gamma ray tracer log is a continuous recording of the measured count rate of gamma radiation across an interval of a well. The count rate is affected by [1] the strength of the source; [2] distance from source of the detector; [3] the amount of shielding. Shielding is proportional to the density and thickness of the material between the source and the detector. Radiation at the strength used in fracture treatments can only be detected for a short distance of about one foot in fluid and even less when shielded by casing, cement and formation. For this reason the radioactivity in a zone should not be interpreted in terms of the quantity of frac fluid injected nor taken as a measure of the depth of fracture penetration. However, it is of interest that through a fractured zone the radioactivity tends to increase with porosity, indicating possibly that more prop agent is retained in higher porosity streaks.

The following procedure is recommended as a guide to obtaining good tracer logs:

1. Use radioactive material throughout the entire fracture treatment at a concentration of no less than 1 mc of iridium 192 per 1,000 lbs of sand or 0.2 mc Zr.Ni.95 per 1000 lbs of sand.
2. Underflush to prevent flushing the RA material too far from the well bore for detection.
3. Circulate the hole to remove suspended fine radioactive particles and remove fill up.
4. Log at the same speed, time constant and sensitivity as the original or base log. A repeat log under these same conditions will verify that the tools are functioning properly and that the hole is free of suspended fine RA particles.

A radioactive tracer can be changed by logging speed. A speed of 20 fpm is preferred for both the original and tracer surveys. A scintillation counter is preferred to less sensitive through-tubing Geiger counter tools.

Tracer surveys and radioactive prop are recommended for at least a few wells within a field to obtain a better picture of the treating pattern. After the pattern is established, the cost may not be justified for all wells. However, the cost could be greatly reduced by running the radioactive propping material in the frac job and logging only when the well does not respond properly. The technique can be extremely valuable in determining the need and direction of workover attempts when it indicates channeling to higher or lower intervals containing gas or water.

PRIMARY CEMENTING

A sound primary cement job is critical in well completion and stimulation. If the cement does not provide isolation between sets of perforations, one zone will fracture initially in multistage attempts and subsequent stages will feed through channeled cement into the same fracture. Or worse, a fracture will occur at some undesired zone well outside the interval selected for treatment. In some instances abnormal gas or water production may indicates this condition; but more often the production results are poor, and due to the many uncertainties involved, are unrecognized as such. All these points were clearly illustrated in multistage fracturing in the North Ward Estes Field at Monahans, Tex.

The three density logs shown on the left of Fig. 8 were obtained from three wells during early attempts at continuous multistage fracturing. On these logs is indicated the extent of travel of radioactive sand which was obtained in the manner described in reference to Fig. 7. The frac fluid and prop are shown to have traveled as much as 150-200 ft above the Queen sand and all sets of perforations communicated, indicating few if any fractures occurred in the pay. Of a group of 14 wells, six had very similar results. This clearly showed that the multistage attempts were failing due to inadequate primary cementing.

Primary cementing practice was altered and the final procedure included:

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