Practical And Economic Aspects Of Hydraulic Perforating

By H. L. ADAMS, JR.
The Western Company

ABSTRACT

Hydraulic Perforating has opened many new avenues in remedial and completion techniques. This paper contains a discussion of the advantages and disadvantages of this process and the economic factors involved. Research data are incorporated which define performance that may be expected. Examples are given of most favorable applications.

DEFINITION

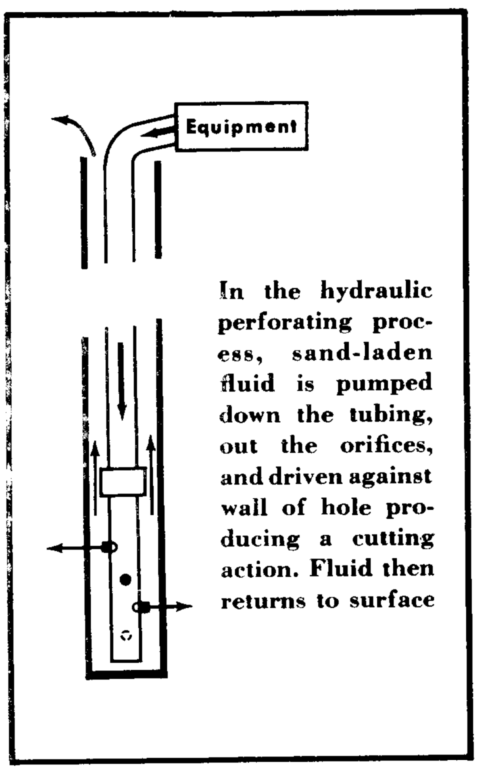
The process involves pumping sand-laden fluid through a set of orifices at a differential pressure of 2500 to 3000 psi. Frac sand has been used as the cutting or eroding medium because of readily available inventories and from the standpoint of economics. Fresh water, salt water, gelled water and lease crude have been utilized as carrier fluids. Fig. 1 indicates wellhead hookup and fluid flow directions.

CALCULATIONS

The procedure to calculate the surface pressure that would be necessary for a given number of perforations at a given differential pressure is as follows:

Rate

The rate necessary for a given size orifice at a given differential pressure can be determined from available charts. This rate times the number of desired perforations determines pump rate.



In the hydraulic perforating process, sand-laden fluid is pumped down the tubing, out the orifices, and driven against wall of hole producing a cutting action. Fluid then returns to surface

Fig. 1

Friction Drop

After the pump rate has been selected, the tubing and annular friction can be determined from existing friction charts.

Surface Pressure

The sum of orifice differential pressure, tubing friction pressure and annular friction pressure is a close approximation of the surface pressure that will be required to perform the perforating process. Of the two, surface pressure and rate, rate is the more important indicator because rate of flow through an orifice versus pressure differential is believed to be more accurate than existing friction charts.

Positioning of Tool

This can be achieved by one of the following methods:

1. Running a through tubing, gamma ray correlation and tubing collar log,
2. Accurate tubing talley corrected for stretch caused by tubing weight,
3. Working from a known bottom or limiting plug,
4. Running a mechanical casing collar locator.

It may be necessary to make corrections for elongation due to pressure or changes in length due to temperature changes after positioning. Pressure stretch will always be a factor except in extremely shallow wells while temperature change corrections are only necessary under extreme ambient conditions. Charts have been published in various handbooks to facilitate the pressure and temperature corrections.

It is desirable to return the sand to the surface and a check should be made to determine whether or not the carrier fluid will remove the sand at the velocity it will be moving in the annulus. The approximate minimum velocities that have been established are: water - 100 ft/min.; 32°API crude - 20 ft/min.; and gelled water - 0.1 ft/min. If the pressure is excessive when the selected rate is established, this would indicate that one or more orifices might be plugged. The reverse situation pressure-wise would indicate that fluid was escaping the tubing or tool at some point other than the orifices.

EXPERIMENTAL PROCEDURE

The process was investigated under the two conditions for which it is used. These, of course, are in open hole and cased hole conditions.

Generally speaking, it has been believed that considerably more penetration could be obtained with this process than was possible with the conventional methods of perforating in a cased hole. This belief was based on surface

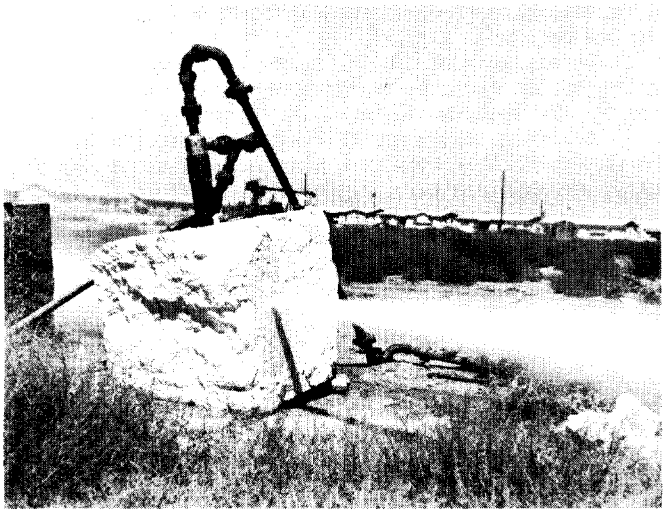


Fig. 2

tests such as Figs. 2 and 3 where an attempt was made to simulate downhole cased conditions.

In making such tests as these, it was difficult to keep from communicating around the pipe and in some cases targets were fractured. On similar targets with sand density, orifice size and differential pressure approximately the same, penetration was inconsistent. The degree of communication appeared to contribute to the inconsistency in penetration. It is possible to obtain fantastic penetration depth during surface tests if all the fluid is lost at any point along the perforation or at the end of the formation perforation.

It was decided to investigate the effect of a noncommunicating target. Fig. 4 represents a target that would permit no communication. The target consisted of J-55 casing with a 2 inch EUE tubing collar welded to be concentric with each perforation that had been made by the Hydraulic Perforating process. Pumping time was only long enough to perforate the pipe prior to welding on the tubing collars.

After closing one end of a length of tubing by welding, it was filled with Cal-seal and allowed to cure for two days. When the length of Cal-seal filled tubing was in place, the distance from the outside surface of the casing to the face of the Cal-seal was 2 inches. When reference is made to penetration of a target, it is with respect to penetration in Cal-seal and not from the outside surface of the pipe.

Fig. 3

Also, it is not intended that these results in Cal-seal can be duplicated in hard rock formation. As can be seen, these results are relative to conditions placed upon the targets.

The target was built to allow investigation of the following:

1. Penetration and hole size comparison with tools of 2-1/2 inch diameter and 3-1/2 inch diameter.
2. The differential pressure that might exist across the casing.
3. The effect of communications by drilling relief holes in the casing.
4. The effect of the carrier fluid on penetration.

After pumping on the target for five minutes with water and sand, it was found that penetration was equal to 3-3/8 inches for both the 2-1/2 inch tool and the 3-1/2 inch tool. Casing perforation size for 2-1/2 inch tool was 33/64 inch while for the 3-1/2 inch tool it was 23/64 inch. After pumping for an additional 15 minutes, the casing perforation for the 2-1/2 inch tool was 33/64 inch, and 1/2 inch for the 3-1/2 inch tool.

Penetration for the 2-1/2 inch tool was 3-1/2 inches compared with 4-1/2 inches for the 3-1/2 inch tool. This test simulated tubing in the hole with a hold-down tool to prevent movement. From these tests, it can be assumed

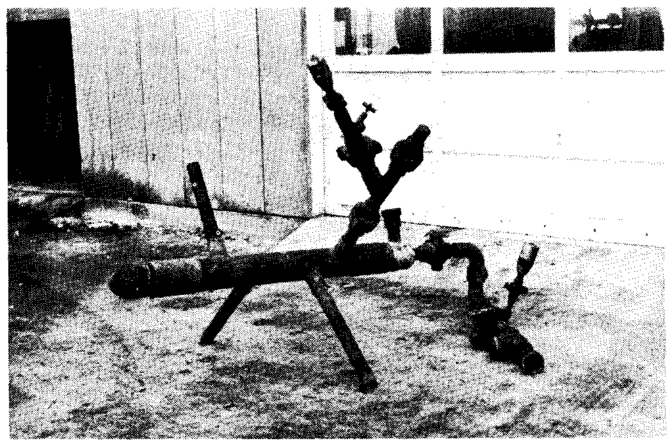


Fig. 4

that additional penetration could be expected with reduced standoff.

Checking Differential Pressure

To check differential pressure across the casing, the target was arranged as in Fig. 4. A "Y" header was attached so that the full force of the jet stream would not be directed at the pressure gauge. The annulus was open to atmosphere. Another pressure gauge was installed in the tubing as indicated. The first pressure reading was made when the perforation was 1/4 inch X 3/16 inch elliptical. The tubing pressure gauge indicated 3600 psi and the target pressure gauge indicated 2000 psi, which represented a pressure differential across the casing of 2000 psi.

A 3/16 inch relief hole was then drilled adjacent to the perforation. With the tubing pressure gauge indicating 3600 psi, the target pressure gauge was indicating 800 psi which again represented a casing differential of 800 psi. A 31/16 inch hole was drilled adjacent to a 1/2 inch perforation and pressures again were checked. Pressure in the target was 150 psi when the tubing pressure was 3600

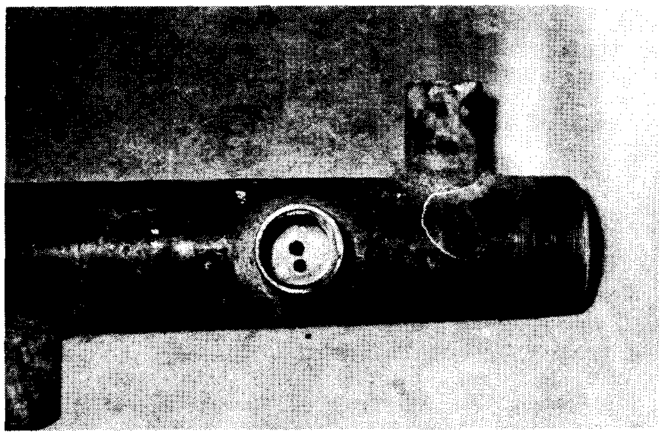


Fig. 5

psi. This explains why targets have fractured soon after the allotted time to perforate the pipe.

After observing the enlargement of the perforation and the effect of the return fluid on the outside of the pipe, it is believed that a similar pressure buildup occurs behind the pipe in actual practice as occurred in the experimental apparatus. Fluid entering the perforation cannot return past the entering jet stream until the pressure buildup is sufficient for counter-current fluid flow past the "flow-bean" effect which the jet stream and perforation represent.

If a sand-laden fluid is pumped, the return fluid will enlarge the perforation until the return velocity of the fluid is reduced to the point where it will not erode the pipe. As the perforation enlarges, the velocity of the return fluid is reduced, thereby reducing the pressure buildup across the casing. Pressure across the casing may approach tool differential pressure for an instant of time due to the maximum restriction of return fluid flow at the time of casing penetration.

The idea has been entertained that it would be possible, with modification of present tools, to transmit pressure across the annulus to the formation with no pressure build-up on the annulus. To do this it would be necessary that the tool remain fixed throughout the treatment and that the diameter of the jet stream be modified.

To determine the effect of reducing the throttling of the return flow through the perforation, a 31/64 inch hole was drilled adjacent to one of two similar perforations. The targets were jetted with sand-laden fluid for 15 minutes. The target which had the relief hole (Fig. 5) had 10-3/4 inches of penetration while the other target (Fig. 6) had 4-1/2 inches of penetration. Fig. 7 indicates the measured

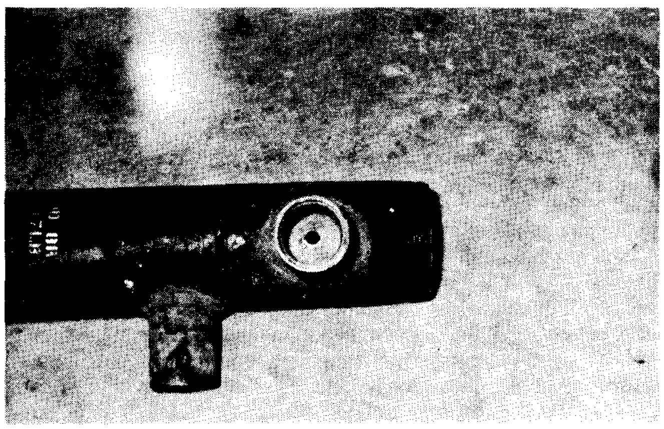


Fig. 6

difference. Seven inches of penetration was obtained through the perforation in Fig. 8.

To determine the effect of carrier fluid on penetration, gelled water was used to compare results obtained on the fresh water test listed above. Penetration was found to be 19-3/4 inches compared to 10-3/4 inches obtained with fresh water. This additional penetration was obtained with three minutes less pumping time.

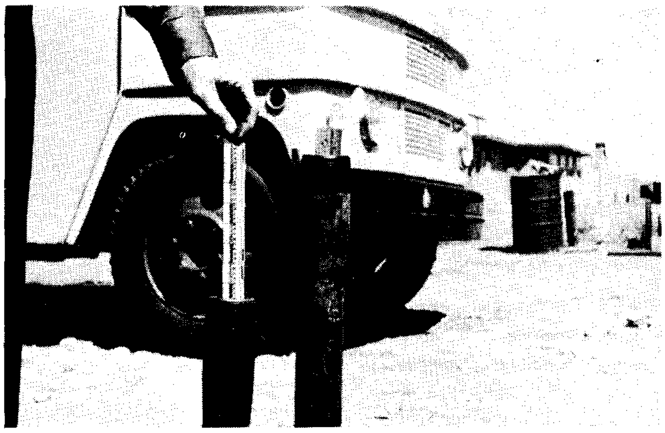


Fig. 7

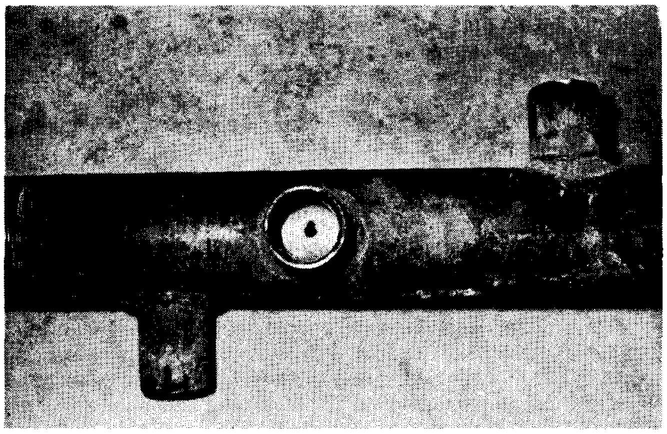


Fig. 8

Since gelled water offers less resistance to shear than water, it is believed this accounts for the difference in penetration. Assuming a similar relationship for shear between lease oil and water, then lease oil would be less effective than fresh water for a carrier fluid. Another advantage in using gelled water is that the annular velocity required to remove sand from the bottom of the hole is greatly reduced over other fluids.

BLOCK TEST RESULTS

Results that have been obtained in casing under a relieved condition are as follows:

Casing was cemented in a granite block and tests were run using water and one pound of sand per gallon. The bottom hole (Fig. 9) resulted after a short pumping period and plugging of the tool, at which time another tool of shorter length was inadvertently used. As shown in Fig. 9, the first perforation transmitted all the back flow soon after the second perforating operation began. This resulted in a relieved situation. After one hour of pumping, 10 inches of penetration in the granite was observed (Fig. 10) with the entrance hole size as shown in Fig. 11. This will be further investigated in the future.

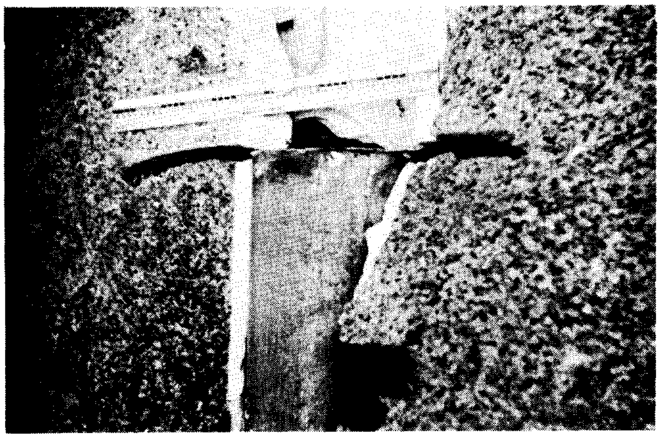


Fig. 9

The following procedure was followed as a means of trying to correlate the above results with those of a shaped charge. Dupont shaped charges were taped to the granite block with a standoff distance of one inch from the apex of the cone to the face of the granite. Results were 5 inches of penetration with a 3/4 inch entrance hole using a Dupont 34W. A Dupont 26A was fired with 3 inches of penetration and 1/4 inch entrance hole size. These charges were shot in air with no steel or casing faceplate.

A test was run using a limestone block illustrated in Fig. 2. This target fractured vertically and eliminated the backflow restriction offered by the pipe. Results are indicated by Figs. 12 and 13. This test indicates more penetration than was obtained with Cal-seal, but the effective diameter of the perforation in the limestone is larger. This will require additional study for there seems to be a relationship between formation perforation diameter and penetration. It was assumed that Cal-seal would permit

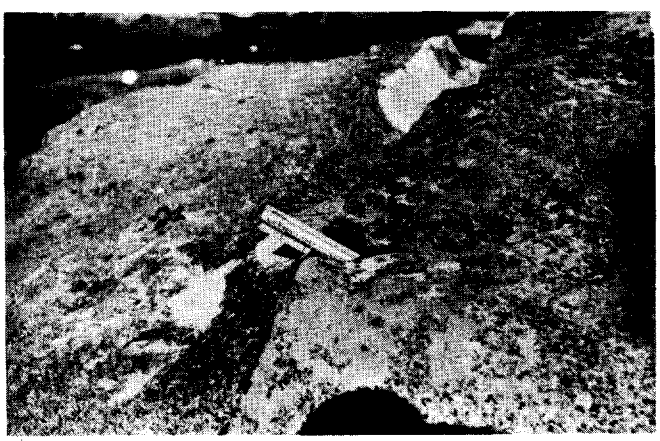


Fig. 10

greater penetration but the perforation diameter in the Cal-seal was limited to the I.D. of the 2 inch tubing.

Relieving The Perforations

The test results on the Cal-seal target which were not relieved and the results on a two parts sand and one part cement target indicate that without relieving the perforations, penetration is in order of 5 to 6 inches in a cased hole. Again, these tests are valid only in shallow wells where negligible stretch is encountered or where a hold-down tool is used. Erosion from backwash on tools that have been used in field jobs indicates that the tools have moved and relieved the resistance to backflow to some degree. For maximum penetration through casing, the job should be planned to allow for relief.

One method to intentionally relieve the backflow resistance would be to increase or decrease surface pressure after pumping for two to three minutes, thus allowing the tool to move down or up as the change in surface pressure affects the pressure stretch of the tubing. Another method would be to rotate the tubing a definite distance at the surface, but the relationship between the rotation at the surface and the tool is questionable under normal conditions. Also, if the separate cuts accomplished by this last method do not communicate, then the purpose for moving the tool has been defeated.

On several jobs the tubing was rotated with power tongs while the pumping operation was going on. This should lend itself to maximum penetration because of the relief that is provided. Self-propelled rotating tools are in the

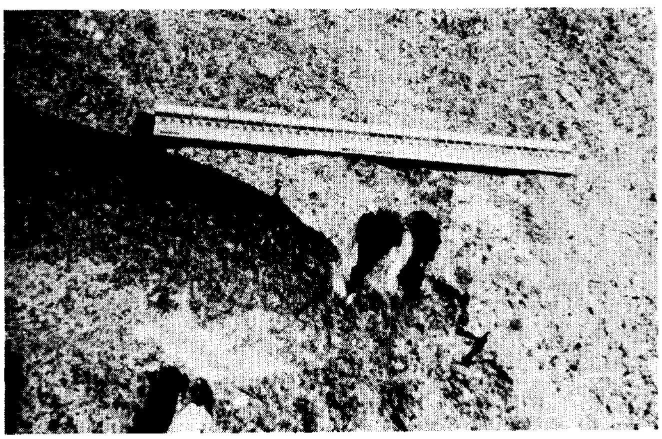


Fig. 11

latest stages of design and have been successfully field tested. Here is a situation where a hold-down tool would not be detrimental to penetration.

Cased hole results would be expected to equal those for open hole conditions on the assumption that the restricting pipe effect was not present on the above tests. On a gelled water test, the casing was cut out as close to the I.D. of the tubing as possible and the test made. Results were equal to those obtained with the relieved perforation test with gelled water, as previously discussed.

In one area where eight similar jobs were performed, there was a definite relationship of backwash wear to

Fig. 12

formation hardness. Hardness was compared by drilling time necessary to drill one foot of formation. Backwash wear was more severe in those cases where drilling time was high. A rotating tool would increase penetration in these cases by eliminating some of the backflow losses.

Fig. 14 represents backwash that can be expected under hold-down tool conditions. Fig. 15 represents backwash effect from a partially relieved perforation as indicated in Fig. 8.

ECONOMIC FACTORS

Hydraulic Perforating cannot make conventional perforating obsolete for economical reasons. All perforating tools have their limits and each has its applications which are best suited to the needs of the oil industry. Generally speaking, on short sections and with plans to frac upon completion of the perforating, there are often cost advantages in selecting the Hydraulic Perforating process.

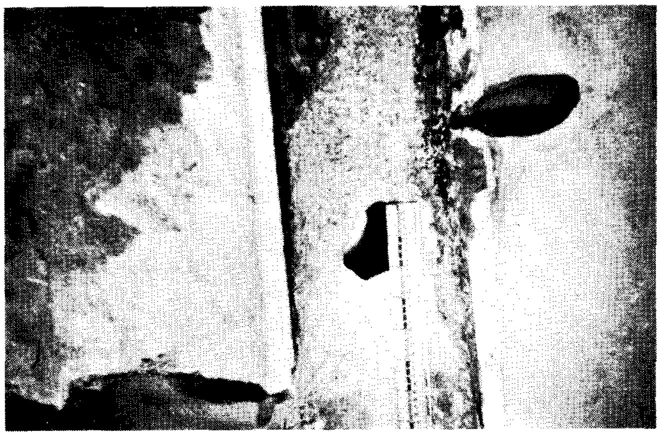


Fig. 13

As is usually the case, it will depend on the individual well conditions and anticipated time that will be needed to complete the job. Time is important since published frac prices are based on time limits.

Where a retrievable bridge plug is used for selectivity, this process makes it possible to perform all phases of the completion with pumping equipment. This means complete utilization of equipment, since one type service is not idle while the other performs its special service. By treating down tubing and annulus, several zones can be treated without pulling tubing. After the bridge plug has been moved and prior to perforating, the plug can be pressure checked to be sure that it is holding. Should it become necessary to spot acid, wash sand from the top of the plug or kill the well, equipment and personnel are available immediately.

Key cost factors, excluding necessary blending and pumping equipment, are the sand, fluid, storage capacity, pulling unit or rig cost, process tool cost, method of positioning the tool, stripper head or blowout preventors, and possibly a swivel.

ADVANTAGES

1. One of the greatest advantages is deeper penetration, especially in small pipe. It might be said that maximum penetration power is available for casing sizes ranging from 9-5/8 inches to 2-7/8 inches whereas conventional perforating power is limited by pipe diameter.
2. Concentration in one plane. For example, it is possible to have six orifices in one plane and this is available for 4-1/2 inch casing and up.

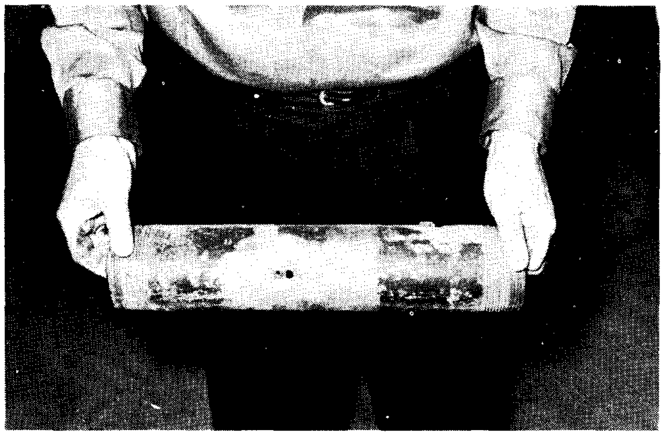


Fig. 14

3. There is no burr left in the pipe following Hydraulic Perforating.
4. When the tool is used in conjunction with a retrievable bridge plug, it has been proved very effective in checking for communications and for "shoot and test" operations.
5. Although differential pressure exists across the casing, there has been no evidence of shattering of cement in any of the targets.
6. Tools have been designed to be left in the hole at very little cost to the operator.

DISADVANTAGES

1. The number of perforations that can be made at any one setting.
2. The high cost when equipment is used only for perforating and no other service is to be performed on the well.
3. If maximum depth of penetration is attempted, then ball sealers are not advisable due to tool position change which would result in irregular holes.
4. The difficulty of positioning the tool as close as wire line measurements afford. However, on a 7500 foot well and spotting with a through tubing log, perforations were found only 4 inches off the desired spot as checked by using a magnetic collar locator.

Precautions

The use of lease oil, in addition to the reduced effectiveness, presents a fire hazard which is magnified due to the circulation requirements.

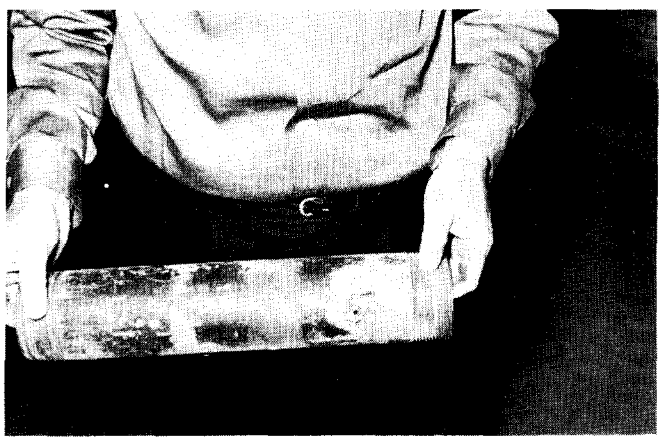


Fig. 15

Sufficient fluid must be on hand to reverse or circulate the sand out of the hole.

Returns must be obtained to eliminate sandouts unless a closed system is utilized and the sand is forced into the formation.

EXAMPLES OF APPLICATION

People in the oil industry have used a lot of imagination insofar as application of the Hydraulic Perforating process is concerned.

One example has given exceptional results on a four well comparison. Two wells were on the "A" lease and two on the "B" lease with comparable open hole well conditions. The wells on "A" lease were broken down with acid and then fraced. The wells on the "B" lease were broken down with acid and followed with the Hydraulic Perforating process using acid and sand.

The sand-laden acid was not returned to the surface but injected into the formation. The rate down the tubing was maintained to keep the differential pressure across the tool at 3000 psi as the casing pressure increased to a treating pressure of 800 psi. All four wells were fraced using the same amounts of fluid, sand and equipment. "B" lease has produced as much oil as "A" lease in less than half the time.

Another example of application was used on a well that had been plugged by gypsum. The open hole had been drilled out and a weak acid treatment was used to no avail. Four wells surrounding this well were flowing. Perforating the 160 foot section with treated water and sand was accomplished by moving the tubing about a foot per minute while pumping through a four orifice tool. The tool in this case was not rotated.

Although returns were good, all cuttings were not returned to the surface. A bit was run to clean up the hole and samples were caught containing gyp and formation. After swabbing the treated water from the formation, which was lost during the perforating, and drillout operations, the well kicked off and flowed.

In other examples, open hole was perforated in one plane with six orifices and then fraced. The operator was convinced that this operation was successful in keeping him out of water and gas that are present in the productive zone. This opinion was not formulated on the results of one well but on the results of several wells.

Several hundred wells have been perforated utilizing this process under many different well conditions. The results have varied from excellent to failures which may or may not be attributed directly to the process.

CONCLUSIONS

Test results indicate that the two controlling factors are pipe restriction and the character of the formation to be perforated.

To be able to accurately predict penetration in any rock is forthcoming. This assumption is based on the belief that formation resistance to erosion is the controlling factor because the pipe restrictions can be eliminated by manipulation of the tubing. The granite test represents one point on the curve, but the other two successful tests have other restrictions placed upon them that keep them from being valid points at this time. Further tests will be necessary to be able to evaluate time versus penetration with the several carrier fluids available.

Present test data indicate that around 20 minutes of pumping time will give 80 to 90 per cent of maximum penetration. The results of pending tests affect to some degree the economics and future of the process. Tests that were anticipated to give definite points on this curve introduced other factors which must be investigated before they can be validated.

We believe when perforating in pipe and using orifices in one plane that this process is instrumental in eliminating communication both in the cement and the formation. The same would hold true for open hole insofar as the formation is concerned.

Like most new processes, it needs some refinement. It is a good contribution to well completion and workover methods and with further developments and study will become a generally accepted process.