

March 30, 1965

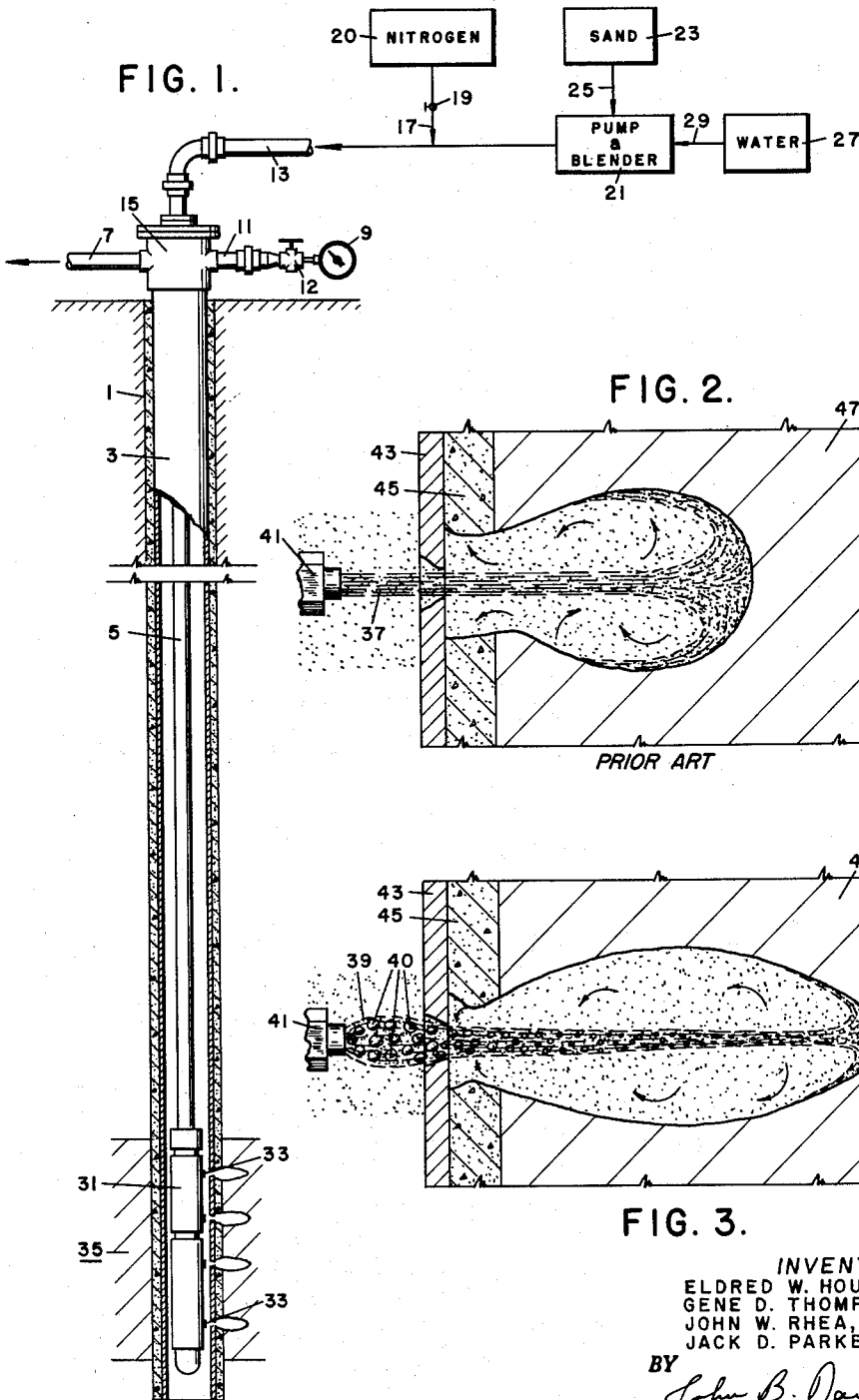
E. W. HOUGH ETAL

3,175,613

WELL PERFORATING WITH ABRASIVE FLUIDS

Filed Aug. 26, 1960

4 Sheets-Sheet 1



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FIG. 4.

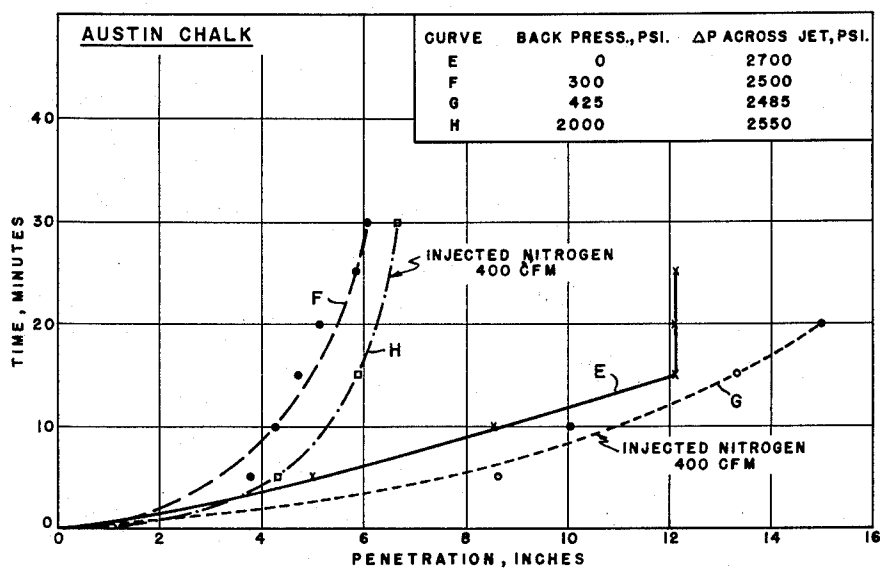
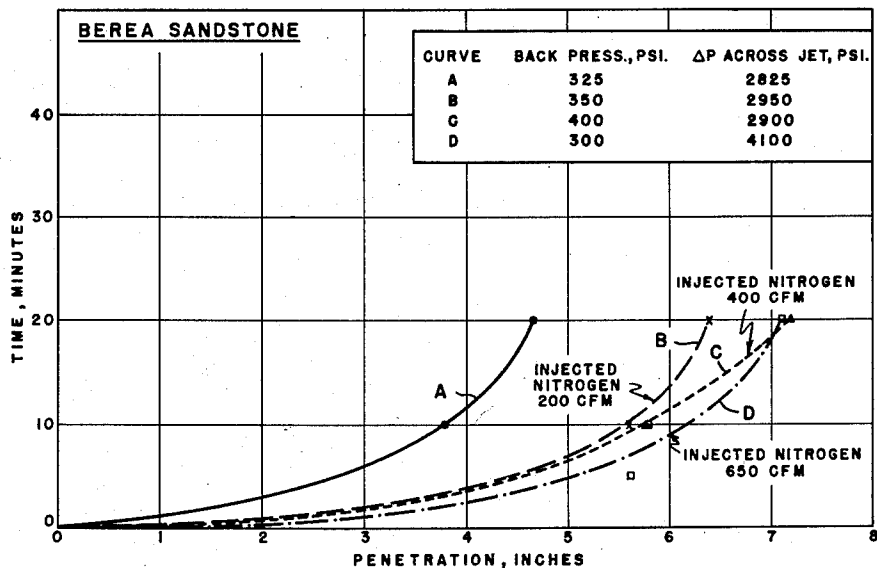


FIG. 5.

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FIG. 6.

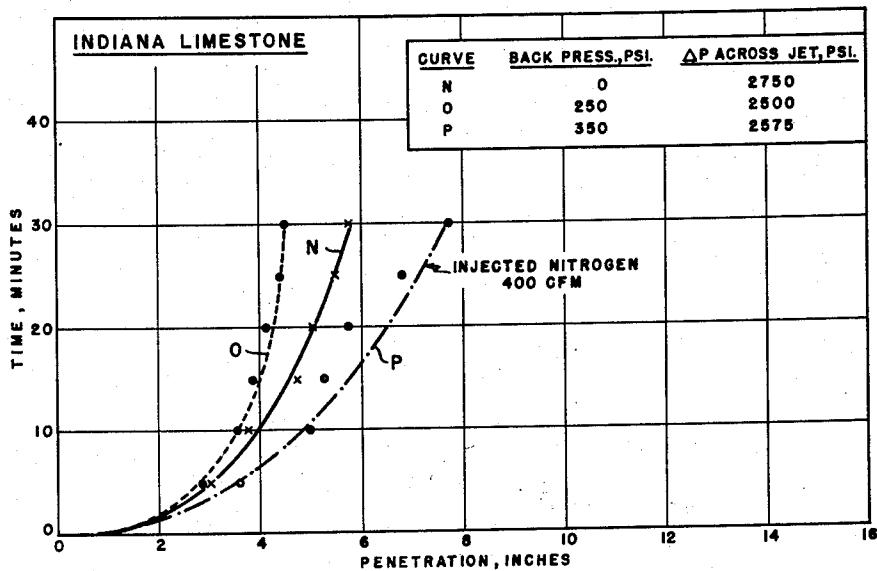
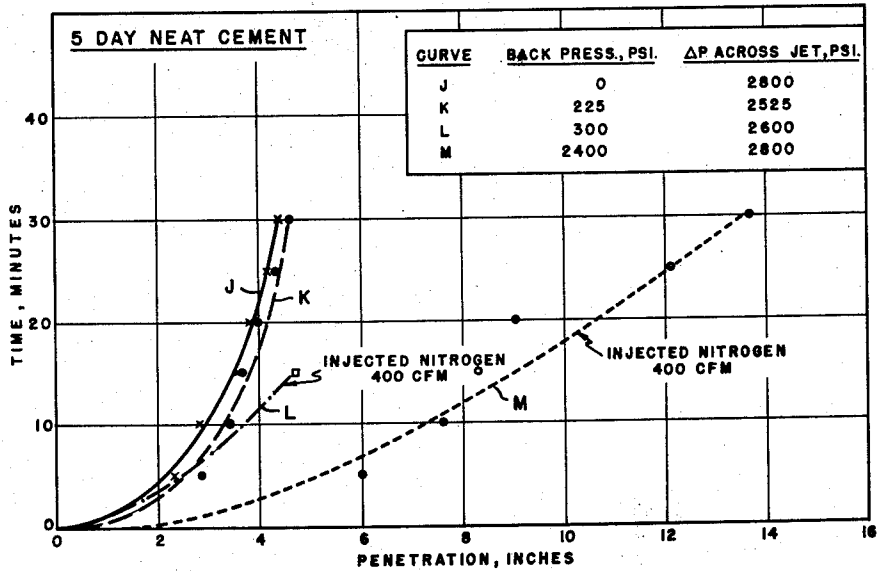


FIG. 7.

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FIG. 8.

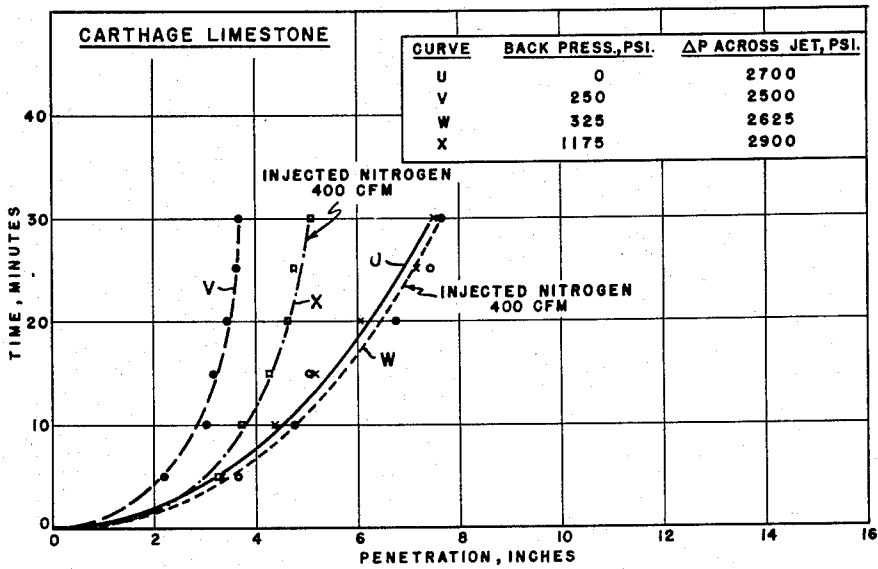
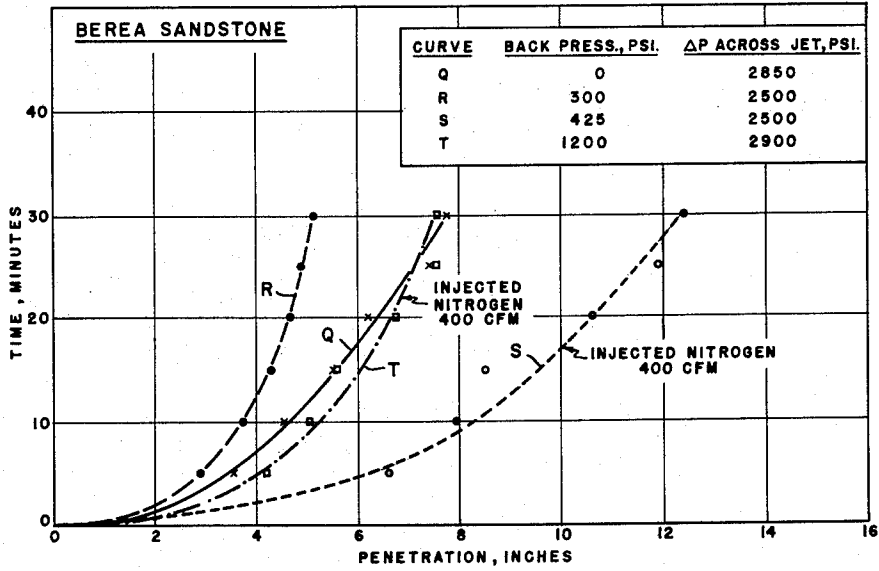


FIG. 9.

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WELL PERFORATING WITH ABRASIVE FLUIDS
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This invention relates generally to perforating techniques for opening fluid communication between a well conduit and an earth formation penetrated by the well, and more particularly to the use of abrasive hydraulic jets for such perforating techniques.

After a borehole has been drilled in the earth for the purpose of recovering oil, gas, and other mineral deposits therein, it is customary to cement a pipe string in the borehole to serve as a liner for the borehole. In order to produce the formation, it then becomes necessary to perforate the pipe, the cement sheath, and the earth formation to open passages for the flow of fluid from the earth formation into the well bore.

Various methods and apparatus have been used in the past for the purpose of perforating wells. One technique that has been found to be successful utilizes an abrasive liquid which is forced downwardly into the well through a tubing string, and which is directed laterally from the tubing string against the well casing by means of specially designed nozzles. The abrasive liquid stream is usually water or oil charged with sand in the ratio of between 1/2 to 3 or 4 pounds per gallon of liquid. The liquid stream is ejected from the nozzles for any desired length of time to abrade the wall of the well casing, the cement sheath therearound, and the productive earth formation from which it is desired to produce formation fluids. The general technique is described in U.S. Patents No. 2,758,653, Desbrow, No. 2,302,567, O'Neil, and No. 2,315,496, Boynton.

The abrasive fluid-jet technique of perforating appears to function quite well under conditions where there is no fluid or hydrostatic back pressure against which the jet must operate and as long as it is possible to have free flow of fluids out of and away from the hole drilled by the abrasive fluid. This is evidenced by the results reported in an article in the Oil and Gas Journal, June 15, 1959, at page 68. However, under well conditions, a very different situation prevails. It has been conclusively determined that the penetration obtained with an abrasive liquid is substantially reduced when the back pressure against which the jet is directed exceeds 20 p.s.i.

In accordance with the teachings of the present invention, the abrasive liquid stream is mixed with a normally gasiform fluid prior to being injected into the tubing string carrying the abrasive liquid down to the earth formation to be perforated. By "normally gasiform fluids" is meant a fluid which is a gas at normal (or atmospheric) conditions of temperature and pressure at the earth's surface. Fluids in this category include hydrogen, nitrogen, carbon dioxide, hydrocarbon gases and the like. The volume of the normally gasiform fluid introduced into the abrasive fluid stream is such that the fluid stream is at least 25 percent saturated with the normally gasiform fluid at the temperature and pressure conditions just upstream from the nozzle through which fluid is directed against the earth formation. By "25 percent saturated" is meant that the liquid, at a given temperature and pressure, contains 25 percent of the maximum volume of gas (measured at standard temperature and pressure) that will go into solution in the liquid at the temperature and pressure of the liquid. The fluid stream is completely saturated with the abrasive fluid for maximum rate of penetration and total penetration.

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However, a 25 percent solubility ratio has been found to be effective. The liquid may be any liquid adapted to dissolve the normally gasiform fluid to be used. Water, either fresh or saline, and diesel oil will be found to be quite effective in this regard. The abrasive agent mixed with the fluid may be sand, emery grains or other hard, abrasive materials.

The invention will be further described with reference to the accompanying drawings wherein:

FIG. 1 is a diagrammatic representation of a well installation for practicing the technique of the present invention;

FIG. 2 is a cross-sectional representation of a perforation being cut by abrasive liquid utilizing prior art techniques;

FIG. 3 is a cross-sectional representation of a perforation being cut utilizing the technique of the present invention; and

FIGS. 4 through 9 are graphs of perforating time in minutes as a function of depth of perforation in inches for a variety of types of cement and earth formation cores under various conditions of back pressure, gasiform fluid injection, and pressure drop across a perforating nozzle.

In FIG. 1 there is shown a borehole 1 drilled from the surface of the earth to a productive earth formation 35. A casing pipe string 3 is shown as having been cemented to the sides of the borehole. A tubing string 5 coextends with the casing pipe string 3 from the earth's surface and is supported at the earth's surface by conventional wellhead apparatus 15. At the lower end of the pipe string there is connected a heavy steel tube 31 similar to a small casing shoe or drill collar. Ports in the heavy steel tube 31 are fitted with hard steel plugs 33 which act as nozzles for directing fluids from the lower end of the tubing and the heavy steel tube 31 laterally at the sides of the casing and the earth formation 35. The tubing string 5 is in fluid communication through the wellhead 15 and a pipe 13 with the output of a high pressure pump and liquid-sand blender 21. The inlet of the pump and blender 31 is connected to a liquid reservoir 27 by a pipe 29, and to an abrasive material (such as sand) reservoir 23 by a pipe 25. Exhaust pipe 7 is connected through the wellhead 15 to the annulus between the tubing string 5 and casing string 3 so that fluids may be exhausted from the annulus into a mud pit or other reservoir. A pressure gauge 9 is connected to the annulus by means of a pipe 11 and valve 12. The apparatus described above is conventional and may be of the type normally used by the Dowell Company for the so-called "AbrasiJet" system of abrasive fluid perforation.

The pump 21 should be capable of pumping abrasive fluid down the tubing string 5 under 2000 to 5000 pounds per square inch of hydraulic pressure. The blender mechanism included with the pump 21 should be adapted to mix sand and water (or other liquid) in the ratio of between 0.5 to 3 pounds of sand to each gallon of liquid drawn from reservoir 27.

A source 20 of high pressure, normally gasiform fluid, is connected to the outlet of pump 21 (or to pipe 13) by means of a pipe 17 and valve 19. The normally gasiform fluid may be hydrogen, nitrogen, carbon dioxide, natural gases such as methane, or other gasiform fluid that is capable of being dissolved in the liquid stored in reservoir 27. When nitrogen is used as the normally gasiform fluid, it may be under a pressure of 6000 to 8000 p.s.i.

When it is infeasible or undesirable to use highly pressurized gases, it is feasible to use a chemical adapted to react quickly with the liquid from reservoir 27 to form the gas in the desired solution ratio. For example, a metal hydride, preferably in powdered form, may be injected into the liquid stream to react with water to liberate hydro-

gen. Examples of complex metal hydrides that may be used for this purpose are lithium aluminum hydride, lithium boron hydride, sodium boron hydride, and sodium aluminum hydride. Examples of primary hydrides that may be used are lithium hydride, sodium hydride, calcium hydride, and potassium hydride. The chemical may be mixed with the abrasive agent in reservoir 23 or may be injected into pipe 13 from a separate container.

When the apparatus is to be operated, the pump is started and the valve 19 is open so that the fluid pumped down tubing string 5 is at least 25% saturated with the normally gasiform fluid. As indicated above, the abrasive liquid stream is preferably completely saturated with the normally gasiform fluid from source 20. The nozzles 33 direct the fluid laterally against the casing 3 and, in due course, holes will be bored through the casing by the erosive or abrasive action of the fluid, through the cement around the casing, and into the earth formation 35. The fluid pumped down the tubing string 5 is maintained at a pressure such that the pressure in the fluid stream at the mouth of each nozzle is less than the bubble-point pressure of the gasiform fluid in the liquid stream in the tubing string. After a suitable interval of time, usually 20 to 40 minutes, the pump may be shut off and the valve 19 closed. If it is desired, the tubing string 5 may be left in the well and used as a production conduit if suitable production packer means (not shown) is connected to tubing string 5 above the heavy steel tube 31.

It has been found that the perforations made in accordance with the present invention are drilled much faster and to a much greater depth than are the perforations formed in accordance with prior art techniques. For an explanation of this statement, reference is made to FIGS. 2 and 3. In FIG. 2 there is shown a perforation being formed in accordance with prior art techniques. The nozzle 41 is shown as having directed an abrasive liquid stream against a casing 43, a cement section 45 and an earth formation 47. In FIG. 3 the abrasive fluid 39 is formed in accordance with the present invention and may consist of the same relative quantities of sand and water into which has been dissolved a normally gasiform fluid, such as nitrogen.

It will be noted that the perforations formed in the sandstone are of different contour. The perforations are assumed to have been drilled for substantially the same length of time. The opening in the sandstone formed in accordance with prior art technique is wider and not nearly as deep as that formed in accordance with the present invention. It is postulated that the action of the prior art fluid jet has been to form a fluid hammer ahead of the jet which is driven against the earth formation without particular effective scouring action by the sand laden fluid 37. In other words, a bank of fluid which is more or less of the same liquid is initially formed which simply is rammed into the earth formation by the fluid jet. The bank of liquid is held in place by the hydrostatic back pressure of the liquid in the well.

Consider now the action of the fluid jet shown in FIG. 3. As soon as the fluid stream begins to leave the nozzle 41, the normally gasiform fluid in the liquid comes out of solution. Shortly after the gasiform fluid has exited from the nozzle 41, large bubbles 40 are formed in the fluid stream. As the bubbles are directed down the fluid jet at the formation, they gradually reduce in size. However, many bubbles remain in the fluid stream to impinge against earth formation. The reason for this phenomenon is believed to be related to the pressure gradient in the jet. Before the fluid passes through the nozzle, the pressure is very high. At the mouth of the nozzle the pressure is at a minimum. As the velocity of the fluid decreases after passing through the nozzle, the pressure within the fluid increases. Bubbles which are formed at the mouth of the jet by the gas coming out of solution are compressed by this pressure increase. When the compressed bubbles reach the end of the fluid stream

their velocity is reduced to zero, and the energy therein is released into the liquid or earth that stops their forward travel. The effect of these bubbles is to create a series of shock waves which induce a spalling attack on the rock present at the liquid boundary at the earth formation that is effective to break up any fluid bank that attempts to form at the surface of the formation in the perforation. Thus, the bubbles and sand particles are able to strike the earth formation rather than to be deflected away from the formation by the fluid bank, as happens when gasiform fluid is not mixed with the abrasive fluid stream. The cross-section of the perforation formed in the earth formation is narrower and far more pointed than the perforation formed by the use of prior art techniques.

From the above discussion it can be seen that the erosion thus is a combination of the erosion produced by the sand particles and erosion by cavitation.

The curves of FIGS. 4 through 9 summarize the results obtained by directing fluid jets at neat cement cores and various types of earth formation cores. The same stand-off distance was used to obtain the data for all of the curves. Various back pressures were produced at the face of the core being tested to simulate the hydrostatic pressure of the borehole fluids as would be found under actual operating conditions in the field. The curves of FIG. 6 were obtained from substantially identical cores of neat cement that had been allowed to age for five days. The curves of FIGS. 4 and 8 were obtained utilizing Berea sandstone cores. The curves of FIGS. 5, 7, and 9 were obtained utilizing cores of Austin chalk, Indian limestone and Carthage limestone, respectively.

A number of conclusions can be reached from the curves of FIGS. 4 through 9. It is readily apparent that both total penetration and the rate of penetration are substantially increased by the use of gasiform fluid injected into the abrasive fluid mixture. This is particularly apparent from the results shown in FIGS. 5, 8, and 9. In the experiments summarized by the curves of each of these figures, a very small back pressure of 300 or 400 pounds per square inch was enough to decrease the total penetration and rate of penetration to between $\frac{1}{3}$ and $\frac{1}{2}$ of the total penetration and rate of penetration, respectively, obtained with zero back pressure.

Furthermore, the use of 400 cubic feet per minute of nitrogen injected into the fluid stream with 300 or 400 pounds of back pressure at the core was enough to increase the total penetration and the rate of penetration to greater than what they were without nitrogen injection and with zero back pressure. While the increase of back pressure to between 1000 and 2000 p.s.i. substantially reduced both total penetration and rate of penetration, the reduction did not reach that obtained without nitrogen injection and with 200 or 300 pounds of back pressure at the core.

Furthermore, from a consideration of the curves of FIG. 4, it can be seen that with the back pressure of 300 or 400 p.s.i. and with various amounts of injected nitrogen, that even 25% or 50% nitrogen saturation was sufficient to substantially increase the total penetration and the rate of penetration from that obtained without nitrogen injection. For the conditions set forth in FIG. 4, 100% saturation was reached at about 375 or 400 cubic feet per minute of injected nitrogen. It is also apparent from the results of FIG. 4 that not very much improvement in total penetration and rate of penetration could be expected by increasing the amount of injected nitrogen past saturation. This can be seen by comparing curves C and D where the results of curve C were obtained using substantially saturated fluid, and the results of curve D were obtained utilizing substantial amounts of nitrogen substantially in excess of that required to saturate the fluid.

It is to be noted that on all curves only those labeled as having "injected nitrogen" were obtained with fluids

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having nitrogen injected therein. Curves A, E, F, J, K, N, O, Q, R, U and V were obtained with no nitrogen being injected in the abrasive fluid.

It can be seen from the results summarized in FIG. 6 that with neat cement substantially the same penetration was realized when the back pressure was increased from zero p.s.i. to 225 p.s.i. without nitrogen injection. The use of nitrogen injection, however, dramatically and unexpectedly increased both total penetration and rate of penetration. Increasing the back pressure to 2400 p.s.i. substantially reduced the penetration and penetration rate but the reduction, as shown by curve M, was insufficient to reduce total penetration and rate of penetration to that obtained with zero back pressure and no nitrogen injection.

The invention is not necessarily to be restricted to the specific structural details or arrangement of parts, as various modifications thereof may be effected without departing from the spirit and scope of the invention.

The objects of the invention having been described above, what it is desired to claim is:

1. An improved method of fluid abrasive-jet perforating the casing of a cased, liquid-containing borehole and a hydrocarbon productive earth formation penetrated by the borehole comprising: positioning at least one fluid nozzle in the borehole at the level of the hydrocarbon productive earth formation; continuously forcing down the pipe string and up the annulus around the pipe string a pressurized, abrasive liquid stream containing a pressurized gasiform fluid soluble in the liquid in said liquid stream to direct at the formation through said at least one nozzle said pressurized, abrasive liquid stream containing a pressurized gasiform fluid; and maintaining the pressure of the liquid stream before it is directed through said nozzle at greater than the pressure required to maintain the pressure in the liquid stream exiting from the nozzle at less than the bubble point pressure of the gasiform fluid in the liquid stream.

2. In a method of perforating a cased, liquid-containing borehole and a surrounding earth formation with a well installation including a pipe string in the borehole, equipped with at least one nozzle at the depth of the formation for directing the pressurized abrasive liquid

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stream laterally of the pipe string at the borehole casing and formation, the improvement comprising: continuously injecting the abrasive liquid stream into the pipe string under high pressure and flowing the abrasive liquid stream up the annulus around the pipe string to the earth's surface; injecting a normally gasiform fluid into the abrasive liquid stream before it is injected into the pipe string at a volume rate sufficient to bring the gasiform fluid-liquid ratio to at least 25% of gasiform fluid saturation in the liquid, and maintaining the pressure of the liquid stream being injected in the pipe string at greater than the pressure required to maintain the pressure in the liquid stream at each opening of said at least one nozzle at less than the bubble point pressure of the gasiform fluid in the liquid stream in the pipe string where- by the gasiform fluid comes out of solution as it exits from said at least one nozzle.

3. The method of claim 2 wherein the gasiform fluid is nitrogen.

4. The method of claim 2 wherein the gasiform fluid is carbon dioxide.

5. The method of claim 2 wherein the gasiform fluid is an aliphatic hydrocarbon and the liquid is a nonhydrocarbonaceous liquid.

6. The method of claim 2 wherein the gasiform fluid is hydrogen.

7. The method of claim 6 wherein the liquid stream is water and the gasiform fluid is generated by injecting a metal hydride into the liquid stream.

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