

Aug. 15, 1967

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3,335,797

CONTROLLING FRACTURES DURING WELL TREATMENT

Filed Dec. 18, 1963

4 Sheets-Sheet 1

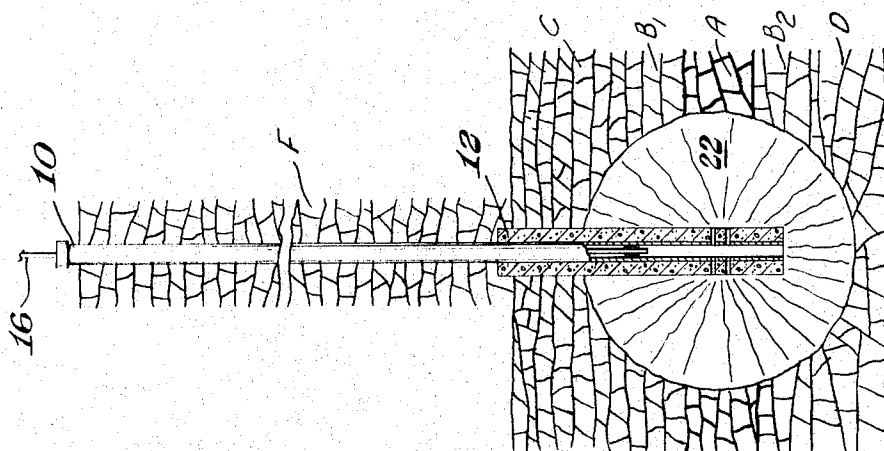


Fig. 3

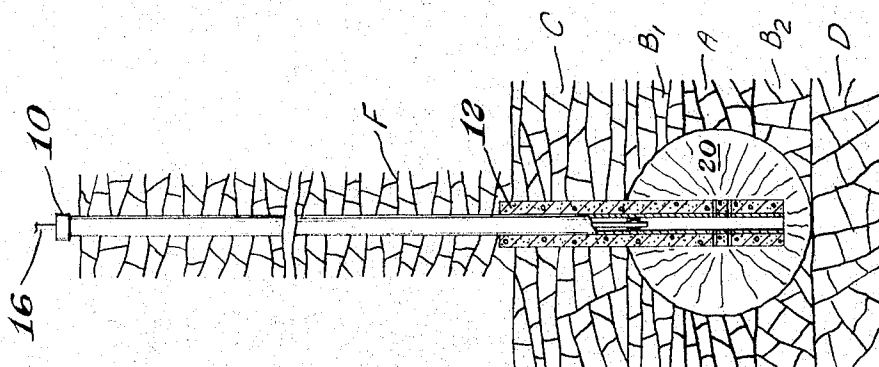


Fig. 2

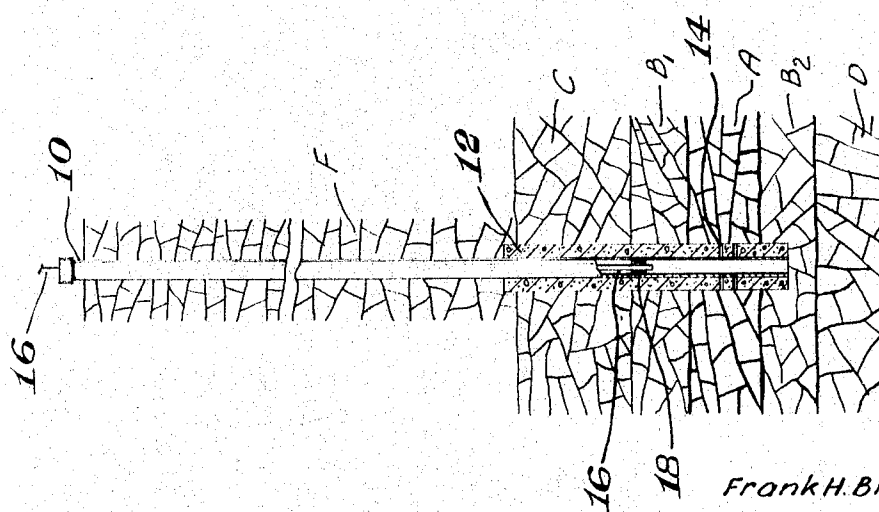


Fig. 1

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4 Sheets-Sheet 2

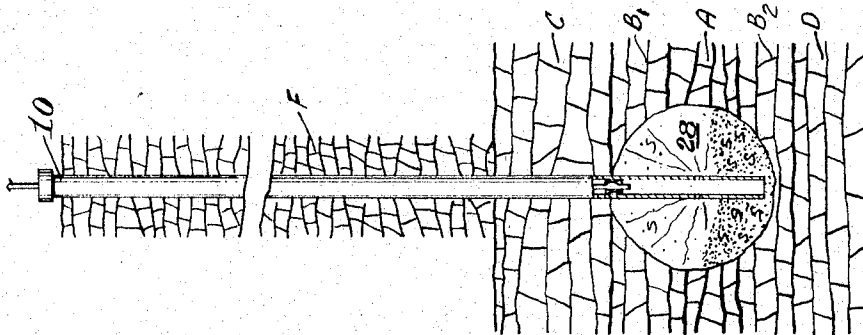


Fig. 6

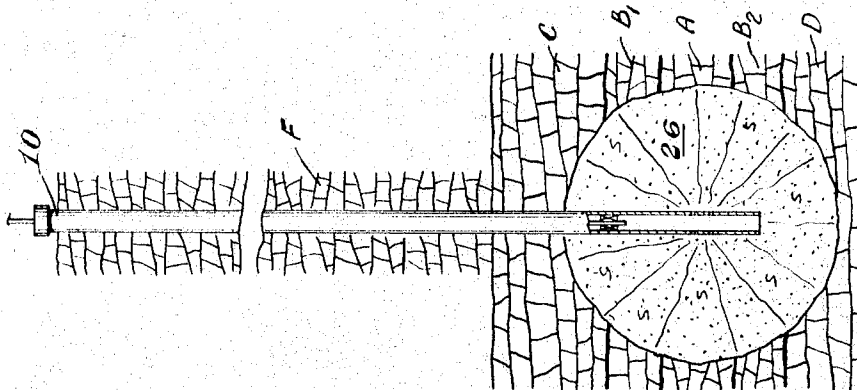


Fig. 5

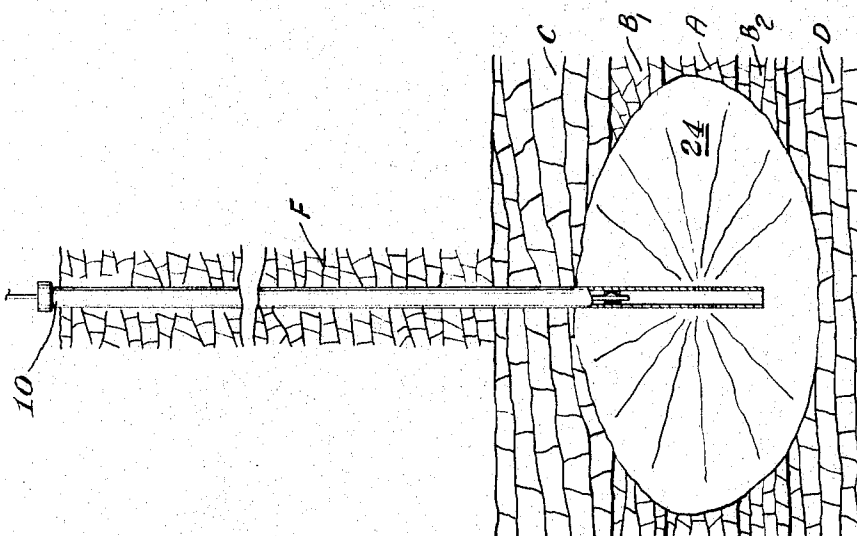


Fig. 4

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4 Sheets-Sheet 3

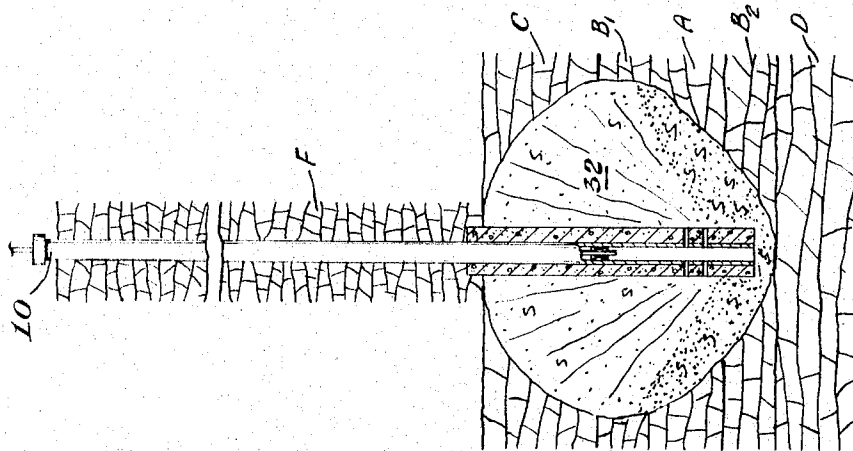


Fig. 9

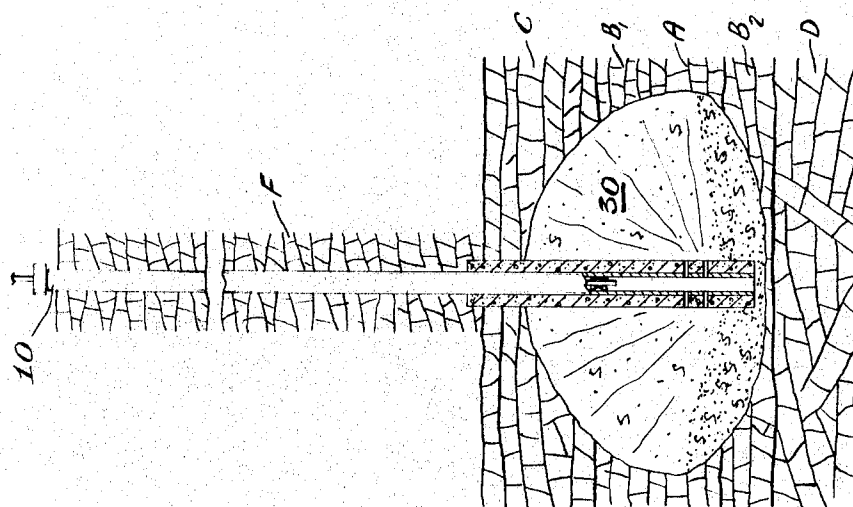


Fig. 8

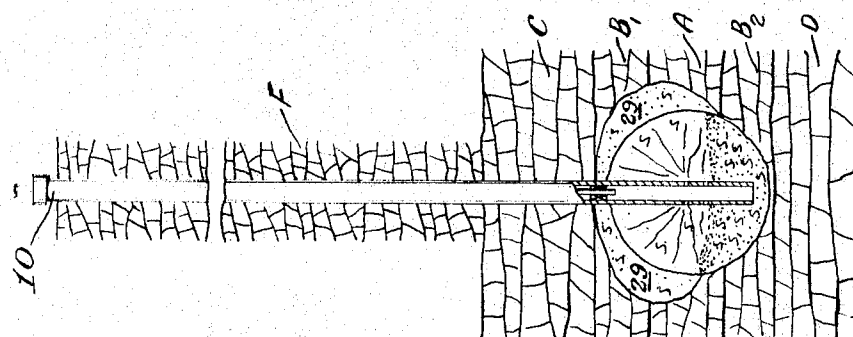


Fig. 7

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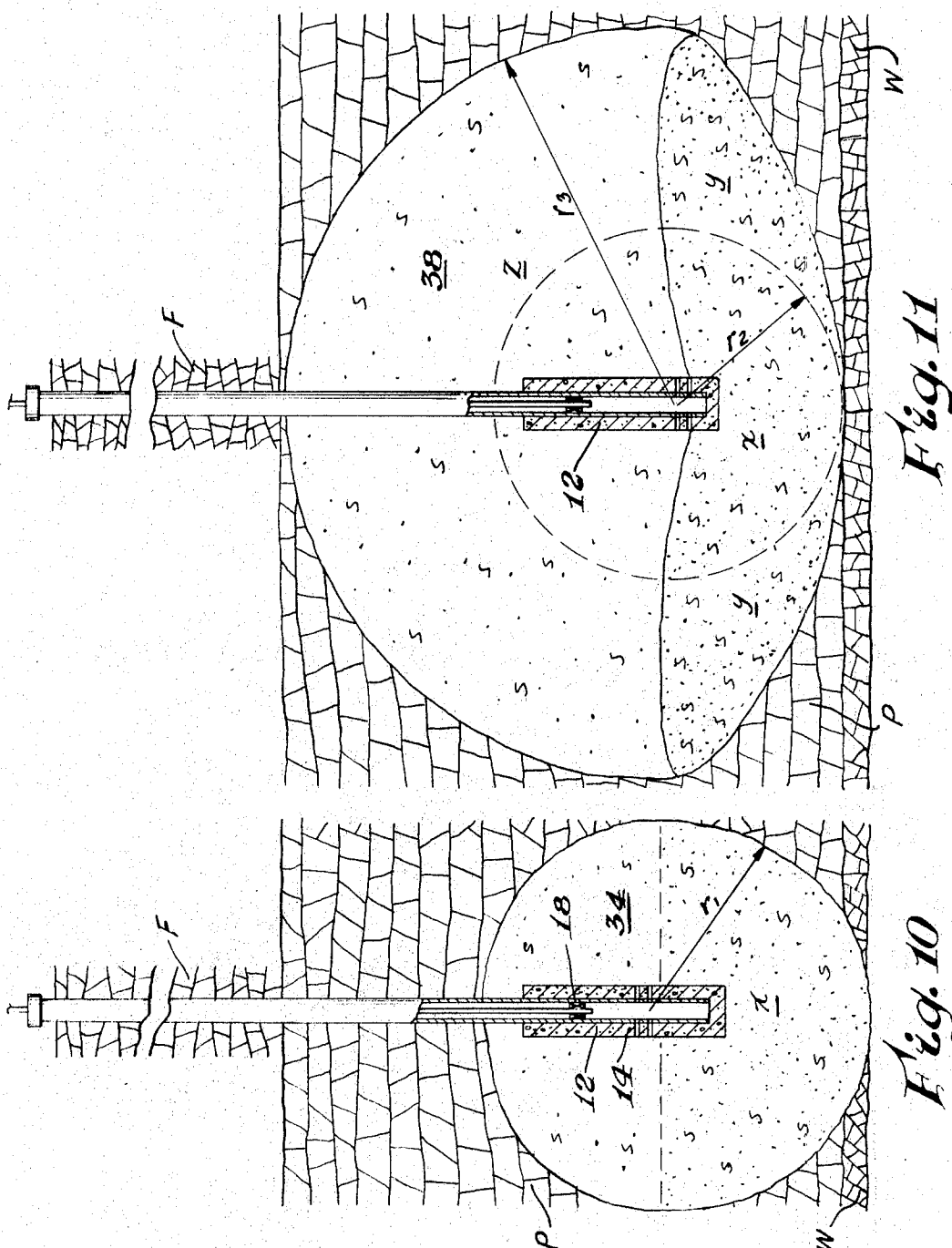
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3,335,797

CONTROLLING FRACTURES DURING WELL TREATMENT

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12 Claims. (Cl. 166—42)

This invention relates generally to hydraulic fracturing of a subterranean formation penetrated by a well and more specifically to a method of controlling the direction of growth of fractures created during hydraulic fracturing.

The flow of desirable fluids, e.g., oil or water from a subterranean formation, often appears depleted when, in fact, a substantial amount thereof remains therein and is prevented by intervening low-penetration rock structures from gaining access to the wellbore. Methods of stimulating the flow of such fluids have been attempted over the years with varying degrees of success.

Hydraulic fracturing has been clearly proven to be a valuable aid to stimulating the rate of production and extending the period of production of fluids from fluid-bearing subterranean formations. It consists, in general, of injecting a liquid down a wellbore penetrating the formation to be treated at a pressure sufficiently great to create fissures, fractures, and the like in the formation to increase the permeability thereof. A basic patent in this area is Reissue Patent 23,733 to Farris. A large number of improvements have been made in the technique of hydraulic fracturing since the issuance of the Farris patent, including the use of improved low fluid-loss liquids and more effective equipment and processes for injecting the fluid down the well and into the formation.

However, hydraulic fracturing, despite its contribution to the art of stimulating flow of fluids from formations through wells and increasing the total amount of fluids recovered therefrom, has not attained a state of performance which is fully satisfactory.

For example, the direction of the fractures which are produced is not adequately controlled, and oftentimes not controlled to any appreciable extent at all beyond selection of the zone to be fractured and the point of injection of the fluid into the zone. The prevailing geologic stresses existent in the formation being treated have heretofore been primarily responsible for the fracture pattern created, supplemented by the inherent strength of the rock comprising the formation being treated.

In fracture patterns, fractures of a wide variety of size, shape, and direction usually occur. They may be substantially vertical, i.e., substantially parallel to the force of gravity, or in other words, generally perpendicular to the earth's surface, or they may be substantially horizontal, i.e., substantially parallel to the earth's surface.

Vertical fractures are often created, due in part to the existence of greater resistance against upward movement of the overburden rock than against some lateral movement of rock.

It is desirable to limit and control the extent of vertical fractures. Unless they are so limited and controlled, vertical fractures may be created which extend into undesirable strata, particularly downwardly, for example, from an oil-bearing interval to a subjacent brine- or water-containing stratum, thereby resulting in undesirable water or brine contamination of the oil. Similarly they may extend into a stratum which is barren of oil.

A particulate water-insoluble material is conventionally intermixed with an aqueous fracturing liquid being injected down a well and into fractures being created in the formation being treated. Sand, granules of plastic, ceramics, metals, seeds, walnut shell and coconut hull are

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used for this purpose. This material is commonly called a propping agent because its main purpose is to prop open fractures created in the formation and permit fluid passage therethrough among the particles through the fracture. Although the particulate propping agent is permeable and permits fluid passage through the spaces among the particles, as opposed to solid rock, passage through the propping agent is hindered to some extent, as opposed to an unfilled fracture.

By proper use of information on the structure, extent, and general nature of a formation, penetrated by a well, which is now available through the use of advanced developments in well logging (including radioactive tracers, photography, and coring) the relative positions and characteristics of various strata can be ascertained prior to treatment. The desired direction and extent of a fracture pattern, therefore, is rather well known but the instrumentality of controlling the direction and extent as desired has been largely lacking. For example, if the progress of fractures can be directed upwardly and outwardly from the point at which a fracturing liquid enters a formation, then the desired pattern may be attained, for example, by introducing the fracturing liquid into an oil-bearing zone located a short distance above a subjacent water zone, and then proceeding to fracture the oil-bearing zone without breaking into the water zone.

I have discovered that by the proper placement of a propping agent, suspended in a liquid during a fracturing treatment, into fractures, passageways, and voids already present or while being created in a formation, the flow of fracturing liquid can be controlled to produce a desired fracture pattern which will, in turn, make possible maximum production of fluid from the formation.

The invention provides a method of controlling the direction of fractures in a formation which meets the long-felt need for a fracture pattern which may progress to a greater extent outwardly and upwardly and to a less extent downwardly from the point at which the fracturing composition enters the formation from the wellbore.

The invention contemplates and encompasses a method of controlling the direction of fractures created in a formation during an hydraulic fracturing treatment which comprises the steps of (1) injecting down the well and into the formation a liquid at sufficient pressure to break down the formation, i.e., to initiate a fracture; (2) inject down the well and into the formation a liquid containing between about 0.1 and about 15 pounds, preferably between about 0.5 and 5 pounds, of a particulate propping agent, substantially insoluble in the liquid, at controlled fracturing pressure to promote fracture growth within the zone desired, at a rate of injection which is great enough to prevent appreciable screening out of propping agent in the wellbore of the well but is not greatly in excess of that necessary to carry the propping agent into the fractures in the formation where it largely falls to the bottom and into the lower portions of the fractures, whereby resistance to further fracturing at the bottom and lower portions of the fracture zone being created is made substantially greater than that which exists at the upper and outer portions of the fracture zone; (3) increasing the rate of injection of the fracturing liquid containing about 0.2 to 7 pounds per gallon of propping agent whereby fracturing liquid is diverted from the lower portions of fracture zone, due to the propping agent deposited therein, and is directed upwardly and outwardly to accentuate fracture growth in those directions.

Increasing the rate of injection in Step (3) over the rate of Step (2) results in a fracture pattern that gradually takes the shape of a semicircle, ellipsoid or fan with the greater axis having a more-or-less horizontal direction.

A mode of practicing the invention is to employ a low

viscosity fracturing liquid in Step (2) which has poor suspending properties so that the propping agent drops out readily as the liquid enters fractures in a formation but to employ a relatively high viscosity fracturing liquid, e.g., gelled water or oil, in Step (3) which has good suspending properties and tends to carry the propping agent a greater distance before it drops out. The viscosity of the fracturing liquid may, of course, if preferred, be gradually increased as the treatment progresses through Steps (2) and (3).

Another mode of practicing the invention is to vary the concentration of the propping agent in such way that it drops out more readily in Step (2) than it does in Step (3) as for example, gradually decreasing the concentration as the treatment progresses.

The formation to be treated, as aforesaid, is advantageously first studied and the desired direction and extent of fractures to be created thereby predetermined.

The rates of injection of the treating compositions during the stages (2) and (3) of the treatment, as supplemented by controlled changes in the nature of the fracturing liquid if desired, will largely determine the fracture pattern in any given geologic formation.

The size of the propping agent to employ is between about 20 and about 60 and preferably between about 20 and about 40. The particle size employed is such that the particles pack together sufficiently to divert subsequently injected liquids but retain some permeability.

Reference to the attached schematic drawing will be helpful to understand and carry out the invention. It consists of a series of figures showing a well penetrating, successively a formation designated broadly as F, gas-bearing zone C, an upper shale zone B₁, oil zone A, a lower shale zone B₂ and water zone D located directly below shale zone B₂. The wellbore of the well is cased with casing 10, the casing being cemented with cement 12 from a point above gas zone C to the bottom of the casing in zone B₂. The casing and the cement are perforated by perforations 14 in oil zone A. The wellbore is provided with a string of tubing 16 and packer 18 positioned at a point above the perforations 14.

FIGURE 1 shows the well just prior to treatment.

FIGURES 2 to 5 are presented for comparative purposes and are not illustrative of the practice of the invention.

FIGURE 2 shows the generally circular fracture pattern 20 that occurs when fracturing is carried out by injecting a fracturing liquid which is substantially free of propping agent in a formation through perforations located at a level near the center of oil zone A, wherein the formation has substantially uniform strength in each of the zones, until fractures have extended through zone A and shale zones B₁ and B₂, but not into water zone D.

FIGURE 3 shows the fracture pattern 22 created when fracturing is carried out as in FIGURE 2 in zones of substantially equal strength, employing a fracturing liquid substantially free of propping agent as in FIGURE 1, until fractures have extended into all the zones.

FIGURE 4 shows the more likely resulting fracture pattern attained where the bedding of the zones C and D offers more resistance to the growth of fractures vertically than horizontally, thereby resulting in elliptical fracture pattern 24 having its longer axis substantially along a horizontal line.

FIGURE 5 shows fracture pattern 26 in strata of the nature of the zones shown in FIGURE 3 wherein a propping agent is suspended in the fracturing liquid. The injection rate employed is sufficient to prevent any appreciable settling of the propping agent in the lower portions of the fracture zone and, as a result, the propping agent is transferred more-or-less uniformly to all parts of the fracture pattern.

FIGURES 6 to 11 illustrate various aspects of the practice of the invention.

FIGURE 6 shows fracture pattern 28, attained follow-

ing the first two steps of the invention, when fracturing a rock formation of substantially uniform structure (of the nature of that shown in FIGURES 1 to 3 and 5), i.e., which offers about the same resistance to fracturing in any direction from the perforations. However, as shown in FIGURE 6 following the creation of an initial fracture according to Step (1) of the invention, the rate of injection of the fracturing liquid containing the propping agent, according to Step (2) of the invention, wherein the rate was only sufficient to carry the propping agent into the fractures, results in a desirable disproportionate amount of the propping agent (indicated by a group of "s's" falling to the bottom portion of the fracture zone). This portion of the fracture zone is plugged to a greater extent than the upper and outer portions causing increased resistance to penetration in the lower portion when additional fracturing fluid is injected down the wellbore and into the formation through the same perforations.

FIGURE 7 shows the direction of growth of the fracture pattern by continued treatment of the formation in accordance with Step (3) of the invention, through a rock structure of substantial uniformity, wherein the rate of injection of the fracturing liquid carrying suspended propping agent, is at a relatively high rate of injection, in accordance with the invention, whereby fracturing is extended principally into the areas indicated by 29.

FIGURE 8 shows fracturing pattern 30 which results when Steps (1), (2), and (3) as shown in FIGURES 6 and 7 are continued, wherein propping agent designated by s's (deposited in the lower part of fractures), deters the subsequently injected fracturing fluid from appreciable further penetration there. As the deposits of propping agent gradually accumulate and the rate of injection is increased, the fractures assume a pattern which slopes upwardly away from the points of entrance and into the fractures. Further injecting of fracturing fluid at a relatively high rate, results in fractures being directed more and more outwardly and upwardly. The fracture pattern is forced to grow only outwardly and upwardly because continual propping agent drop out at the bottom of the growing fracture plugs off downward growth. The propping agent drops at the outer reaches of the fracture because the fluid flow rate in the fracture slows as the distance from the well perforations increases. The resulting fracturing pattern 30 is suggestive of an ellipsoid wherein the lower curvature or arc of the major axis is somewhat flattened.

FIGURE 9 shows the general shape of the fracture pattern as the treatment in accordance with Step (3) of the invention continues, wherein the propping agent is deposited gradually outwardly and upwardly from the points of entrance of the fracturing liquid, giving the pattern a distended upper portion. The resulting shape 32 somewhat resembles a fan.

FIGURES 10 and 11 are shown for purposes of illustrating a manner of calculating the amounts of materials to employ in a well treatment according to the invention, after a study of a log of the well.

FIGURE 10 shows an oil-producing zone P directly above water zone W of a formation. Perforations 14 are located a predetermined distance above water zone W. Fracture pattern 34 shows the general shape that would result, by following Steps (1) and (2) of the invention when a formation of substantially uniform strength wherein fracturing would progress substantially the same distance in all directions (indicated by r_1).

FIGURE 11 shows the fracture pattern, created in zone P when Steps (1) and (2) are followed by Step (3) according to the invention.

The following example, when read in reference to FIGURE 11, illustrates the practice of the invention.

A formation, penetrated by a well, is required to be fractured in oil-producing zone P located just above water zone W as shown. Zone P is 200 feet thick. The well is cased and provided with tubing and supply lines, as shown

connected as necessary to sources of fracturing liquid, propping agent and pumping means not shown of the type known in the art. The casing contains perforations 14 at a distance of 25 feet above water zone W.

It is desired, after initiating a fracture in accordance with Step (1) of the invention, to create a circular fracture and to fill the void corresponding to area X shown in FIGURES 10 and 11. The fracture is calculated to be 0.1 inch wide and to have an area of πr_1^2 which is $3.1416 \times (25)^2$ or about 1960 square feet. The fracture is estimated, based upon measurements of fractures commonly produced, to be about 0.1 inch or 0.0083 foot wide. Thus, the fracture void space is expressed by $0.0083 \times 1960 = \text{about } 16 \text{ cubic feet}$.

A sample taken from the formation shows it to have a permeability of 0.5 millidarcy and a porosity of 15%.

From field engineering manuals it is determined that a fracture of the area given above in a formation having the permeability and porosity stated above, when employing water as the liquid fracturing medium, requires 750 gallons at an injection rate of 3 barrels per minute. Among field engineering publications particularly useful for reference is Drilling and Production Practice (1957), published by the American Petroleum Institute, Dallas, Texas, particularly pages 261 to 270.

The amount of 20-40 mesh sand required to fill the void of area X, being the lower half of the circular fracture, is about 8 cubic feet, half the volume of the void. The 20-40 mesh sand weighs about 104 pounds per cubic foot; therefore about 832 pounds of sand are required.

Accordingly, step (2) of the invention is carried out by injecting 750 gallons of water containing, suspended therein, a total of 832 pounds of 20-40 mesh sand at a rate of 3 barrels per minute.

The treatment then proceeds with Step (3). Reference to FIGURE 11 shows that the calculated fracture to be created will extend from perforations 14 to the top of zone P, a distance of 175 feet and about the same distance horizontally. However, due to the sand deposited in area X, growth of fracture downwardly is inhibited. Growth, therefore, is only upwardly and outwardly, thus avoiding fracturing into water zone W. Step (3) is carried out at a high rate of injection with a liquid, preferably gelled, containing propping agent, although the propping agent content thereof may vary from that of Step (1), e.g., it may be somewhat less. As fracturing proceeds according to Step (3), propping agent is deposited to some extent in each of areas Y and Z, but the deposition in area Y is greater than in Z, as discussed earlier with respect to FIGURE 8.

The amount of fracturing liquid and propping sand required for Step (3) may be calculated as follows:

Since area Z is roughly a half circle having a radius r_3 of 175 feet, the area of one face of a vertical fracture therein is

$$\frac{3.1416 \times (175)^2}{2}$$

or 48,200 square feet.

Area Y, together with area X, resembles an isosceles triangle having a base of 350 feet, i.e., 2×175 feet, and an altitude of 25 feet. Accordingly, area $X+Y = \text{about } 4400$ square feet and Y is $(X+Y) - X$ or

$$4400 - \frac{1960}{2} = 3420$$

square feet. The total fracture area to be evaluated in Step (3) is the sum of area Z and Area Y, $48,200 + 3420 = 51,620$ square feet.

To attain the objective of the third step of treatment (employing a gelled liquid having a fracturing fluid co-

efficient of 1.5×10^{-3} feet per minute plus a 2-milliliter spurt loss), it is found that an injection rate of 15 barrels per minute, to supply a total of 12,000 gallons of fracturing liquid, is required. The significance and method of calculating fracturing fluid coefficient is described in Drilling and Production Practice cited above at pages 262 to 265.

It is also calculated that the sand needed for areas Y and Z is 6000 pounds, a concentration of 0.5 pound per gallon, an acceptable concentration of propping agent in accordance with the hydraulic fracturing art.

The three steps, as thus illustrated, may be summarized as follows:

Step (1), wherein fracturing was performed at a pressure just sufficiently high to initiate a fracture or create a breakdown of the formation;

Step (2), wherein 3 barrels liquid per minute were injected to provide 750 gallons of water containing 832 pounds of sand;

Step (3), wherein 15 barrels of liquid per minute were injected to provide 12,000 gallons of liquid containing 6000 pounds of sand.

The following example is illustrative of a fracturing job which was carried out in an oil-producing field; the formation to be fractured was penetrated by a well having a total depth of 4953 feet and cased with a $5\frac{1}{2}$ -inch casing to a depth of 4853 feet leaving 100 feet of open hole below the casing. The treatment was carried out by first plugging back the well at a depth of 4928 feet with cement. The well formation was then notched at a depth of 4924 feet, to cause the initiation of a fracture at this level as taught in United States Patent No. 2,699,212. A water zone existed at a distance of 40 feet below the 4924 foot level at which fracturing was to be initiated.

The formation was then fractured as follows: Step (1) (Initiation Stage). 500 gallons of fresh water were injected at a pressure exceeding the fracture initiation pressure for the formation.

Step (2) (Orientation Stage). 500 gallons of fresh water, containing suspended therein 750 pounds of 20 to 40 mesh flint sand, was pumped down the well and into the formation at a rate of 2 barrels per minute. This was an injection rate that provided for deposition of sand in the lower portions of the fractures.

This step was followed by an optional intermediate step wherein 500 gallons of fresh water containing substantially no propping agent were pumped down the well and forced into the formation at a rate of 2 barrels per minute. This was for the purpose of insuring sufficient time for the sand used in Step (2) to deposit in the lower half of the fracture.

Step (3) (Extension Stage). 16,000 gallons of 15% aqueous HCl containing 0.55% by weight of a limited crosslinked polyurethane polymer as described in copending application Ser. No. 208,252 by Norman F. Carpenter, filed July 9, 1962, gelled by admixture therewith of 0.44% by weight of karaya gum and containing, suspended therein 15,000 pounds of sand, were pumped down the well at the rate of 9 barrels per minute. This was done definitely above fracturing pressures and at a rate to cause the sand to be deposited well out from the notch.

Thereafter as a further optional step, another 16,000 gallons of the acid composition as prepared above but containing no sand or other propping agent, were pumped down the well at a rate of 9 barrels per minute, followed by 14,000 gallons of fresh water containing no sand at the rate of 8.5 barrels per minute, thereby forcing the fracturing liquid containing sand injected during the third step back into the fractures and recesses located upwardly and outwardly from the notch. The maximum pressure attained during the fracturing treatment was 2900 p.s.i.

The well was then shut-in at a pressure of 1300 p.s.i. After a period of about 24 hours, the well was put back in production. Shortly thereafter, and each day for six successive days, making intervals of about 24 hours

between measurements, the rate of flow of oil was measured. The results are set forth in the table below:

TABLE

Time of Testing after Well was Put Back in Production	Barrels of Oil per Day	Barrels of Water per Day
First Day.....	21	20
Second Day.....	101	23
Third Day.....	192	291
Fourth Day.....	153	184
Fifth Day.....	147	165
Sixth Day.....	155	170
Seventh Day.....	117	129

Periodic checks of the rate of flow thereafter showed no appreciable change from the rate of flow of the tenth day, viz., about 100 barrels of oil and about 110 barrels of water, indicating that the well has stabilized at this rate of flow. The continued rather high water outflow of the well was determined by chemical analysis of the water to be due largely to flooding water reaching the output well rather than native underlying formation water; this well was part of a unitized production system wherein water was being injected down injection wells and some of this water was reaching the output well.

Reference to the example shows that fracturing a well in accordance with the invention was highly successful in stimulating fluid flow from the well.

A preferred mode of procedure in carrying out the well treatment in accordance with this invention is to initiate a fracture in the formation using a liquid containing no propping agent, as set forth heretofore. However, this initiation stage may be combined with the following orientation stage by admixing a propping agent to the liquid of the orientation stage, or conversely by simply omitting the initiation stage and initiating the fracture with the liquid and prop of the orientation stage, and proceeding directly with the orientation stage. This combination of the first and second stages is satisfactory in accomplishing the purpose of this invention but often is not done because of ensuing problems in removing propping agent from the borehole of the well if mechanical or physical problems are encountered and a fracture initiation is not accomplished.

Having described my invention what I claim and desire to protect by Letters Patent is:

1. In the method of fracturing a subterranean formation penetrated by a well employing a fracturing liquid, the improvement which comprises: (1) initiating a fracture in the formation by injecting down the well and into the formation at fracturing pressures a first liquid, (2) injecting a second liquid containing between about 0.1 and 12 pounds of a particulate propping agent, per gallon of said second liquid, said agent being substantially insoluble in liquids employed in the fracturing treatment and in formation liquids, having a density greater than that of said liquids at a rate of injection which is sufficiently high to prevent screening out of the propping agent in the wellbore but at a rate which is not substantially greater than that necessary to carry the propping agent into fractures whereby the propping agent drops to the bottom of the fractures to inhibit subsequent fracturing at the bottom of the fracturing zone, said propping agent having a particle size such that it packs together sufficiently to divert subsequently injected liquids but retains some permeability and (3) injecting down the well and into the formation a third liquid containing between about 0.25 and 7 pounds of a particulate propping agent substantially insoluble in liquids employed in the fracturing treatment and in formation liquids, per gallon of said third liquid, at a rate of injection which is greater than that at which said second liquid was injected whereby

said third liquid is diverted from the bottom portions of the fracturing zone to create fractures extending principally outwardly and upwardly from the point of entrance of the fracturing liquids into the formation.

2. The method according to claim 1 wherein said second liquid is a low viscosity liquid and the viscosity of said third liquid is greater than that of said second liquid.

3. The method according to claim 1 wherein at least one intermediate liquid containing substantially no propping agent is injected down the well after the injection of said second liquid and before the injection of said third liquid.

4. The method according to claim 1 wherein said propping agent is a 20 to 60 mesh size flint shot sand.

5. The method according to claim 1 wherein the rate of injection of said third liquid is between about 2 and about 20 times the rate of injection of said second liquid.

6. The method according to claim 1 wherein the rate of injection is gradually increased during the injection of said third liquid.

7. The method according to claim 1 wherein said second liquid is substantially water.

8. The method according to claim 1 wherein said third liquid is gelled water.

9. The method according to claim 8 wherein said gelled water consists essentially of an aqueous solution of between 0.1 and 0.6% by weight guar gum.

10. The method according to claim 1 wherein the concentration of said propping agent in said first liquid is greater than the concentration of propping agent in said second liquid.

11. The method according to claim 10 wherein the concentration of propping agent during both Step (2) and Step (3) is generally gradually decreased to a concentration not less than 0.5 pound per gallon of liquid employed.

12. In the method of fracturing a subterranean formation penetrated by a well employing a fracturing liquid, the improvement which comprises: (1) initiating a fracture in the formation by injecting down the well and into the formation at fracturing pressures a first liquid containing between about 0.1 and 12 pounds of a particulate propping agent, per gallon of said first liquid, said agent being substantially insoluble in liquids employed in the fracturing treatment and in formation liquids at a rate of injection which is sufficiently high to prevent screening out of the propping agent in the wellbore but at a rate which is not substantially greater than that necessary to carry the propping agent into fractures whereby the propping agent drops to the bottom of the fractures to inhibit subsequent fracturing at the bottom of the fracturing zone and (2) injecting down the well and into the initiated fracture in the formation a second liquid containing between about 0.25 and 7 pounds of a particulate propping agent substantially insoluble in liquids employed in the fracturing treatment and in formation liquids, per gallon of said second liquid, whereby said second liquid is diverted from the bottom portions of the fracturing zone to create fractures extending principally outwardly and upwardly from the point of entrance of the fracturing liquids into the formation.

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