United States Patent

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[72] Inventor **Elmer H. Timmerman**
Littleton, Colorado

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[73] Assignee **Shell Oil Company**
New York, New York
a corporation of Delaware

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[54] **METHOD OF INTERCONNECTING A PAIR OF WELLS EXTENDING INTO A SUBTERRANEAN OIL SHALE FORMATION**
6 Claims, 9 Drawing Figs.

[52] **U.S. Cl.** **166/271,** 166/259, 166/272, 166/281

[51] **Int. Cl.** **E21b 43/24,** E21b 43/26, E21b 33/13

[50] **Field of Search** 166/281, 308, 283, 271, 272, 303, 259, 256, 295

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Primary Examiner—Stephen J. Novosad
Attorney—Louis J. Bovasso and J. H. McCarthy

ABSTRACT: A method of creating horizontal fractures and of interconnecting at least a pair of wells extending into a subterranean oil shale formation by fracturing each well and injecting a solidifiable fluid into at least one of the fractures and maintaining the fluid at substantially a fracture-extending pressure until the fluid solidifies and plugs the fracture. At least one well in which at least one preceding fracture has been formed and plugged in like manner is refractured and at least one of the fractures is extended until the fractures intersect or intersect the wells so that fluid may be pumped through a fracture path from one of said wells to the other.

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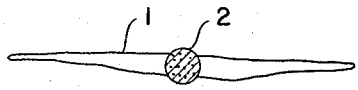


FIG. 1

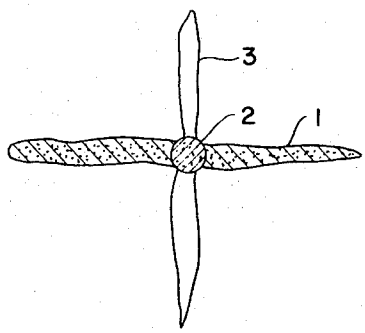


FIG. 2

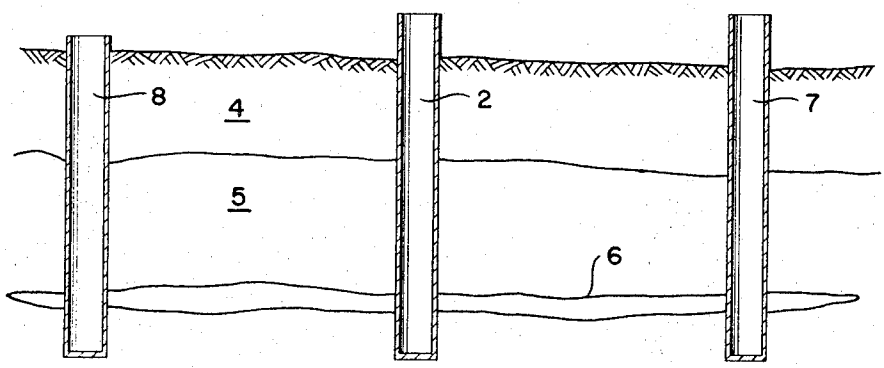


FIG. 3

INVENTOR:
E. H. TIMMERMAN
BY: Louis J Bovasso
HIS ATTORNEY

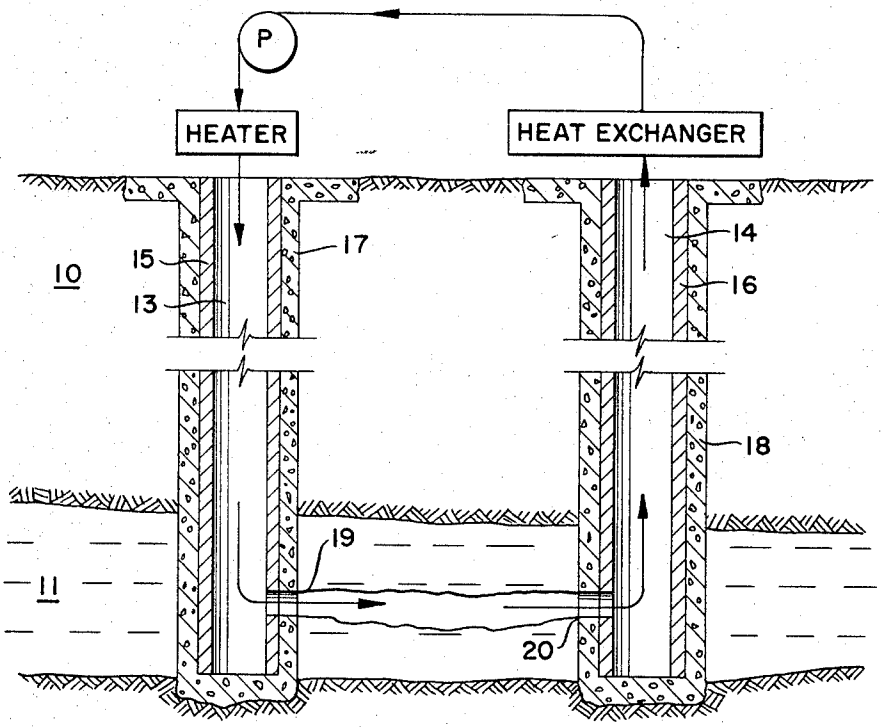
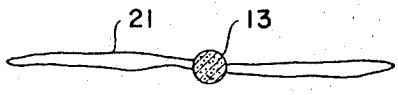


FIG. 6



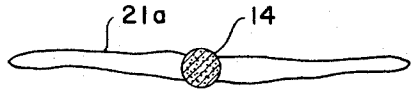


FIG. 4

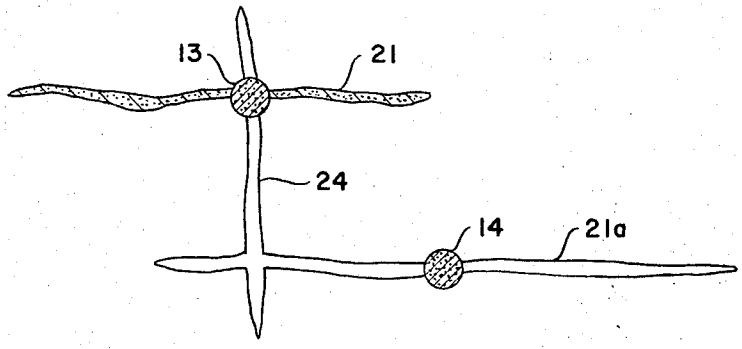


FIG. 5

INVENTOR:
E. H. TIMMERMAN
BY: Louis J Bovasso
HIS ATTORNEY

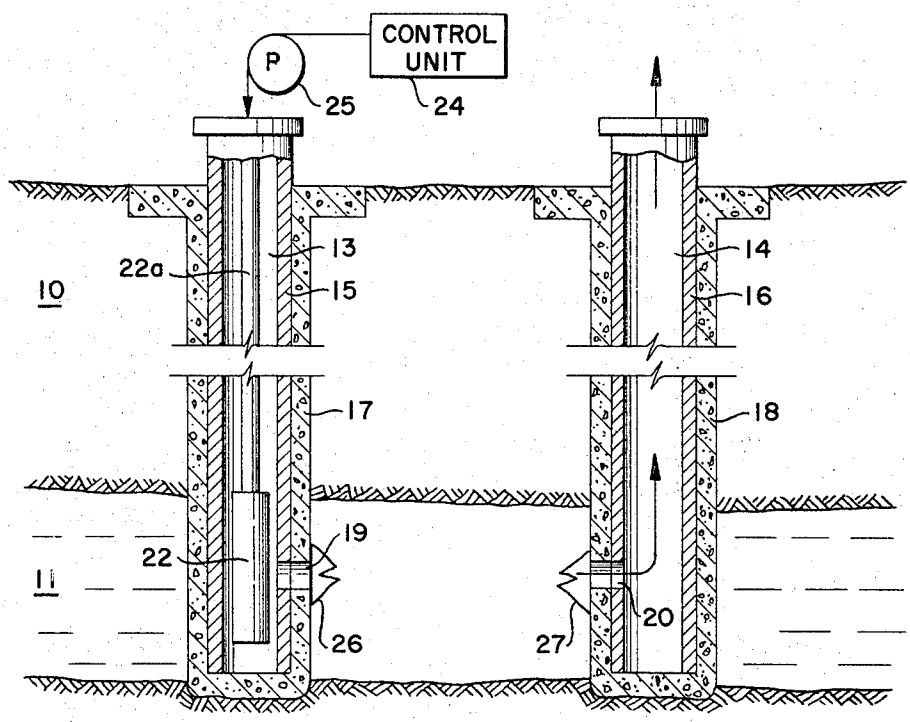


FIG. 7

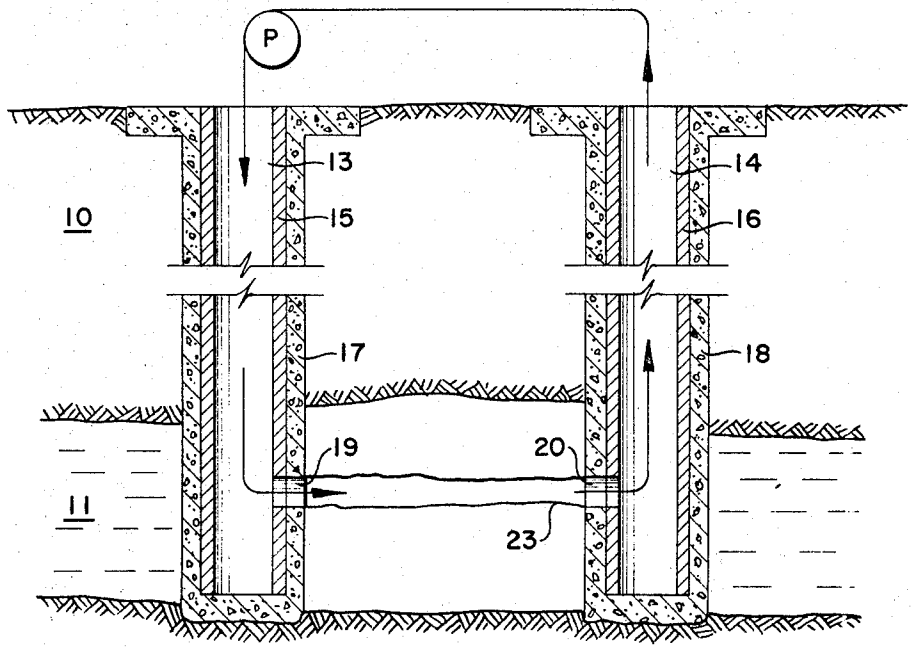


FIG. 8

INVENTOR:
E. H. TIMMERMAN
BY: Louis J. Bovasso
HIS ATTORNEY

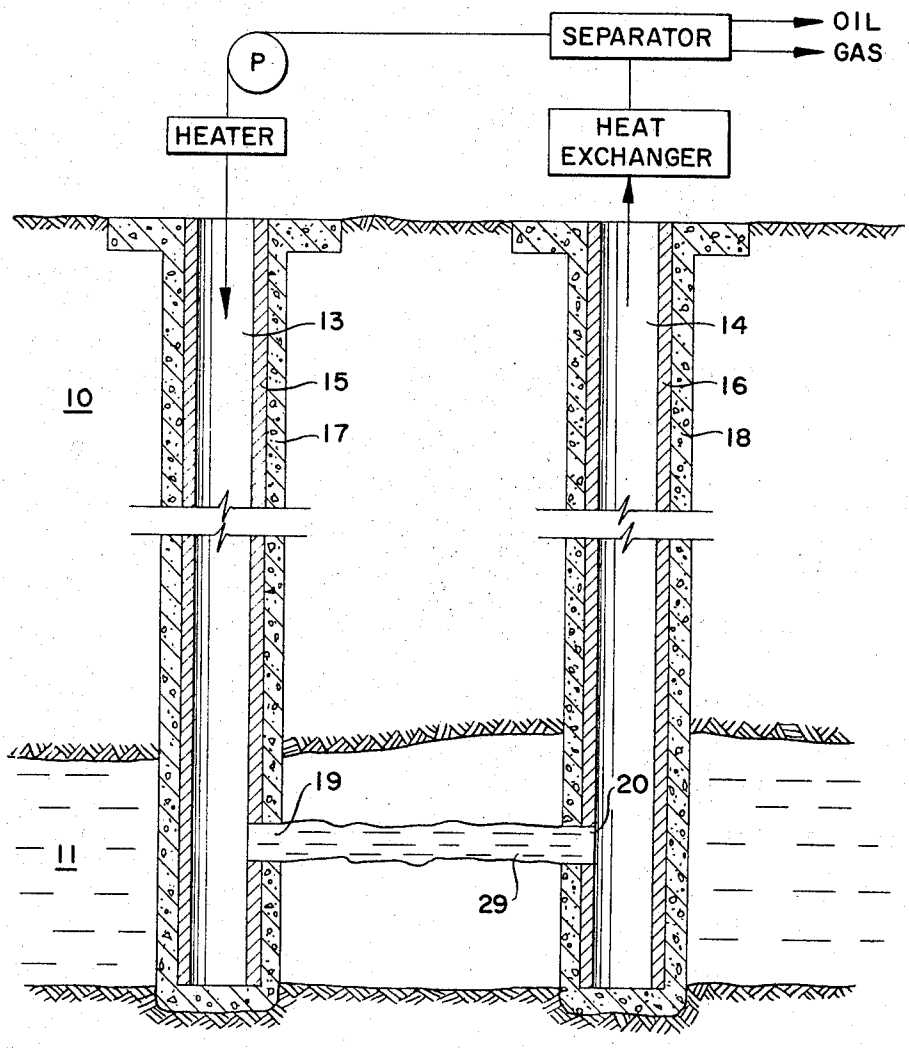


FIG. 9

INVENTOR:
E. H. TIMMERMAN
BY: Louis J Borrasso
HIS ATTORNEY

METHOD OF INTERCONNECTING A PAIR OF WELLS EXTENDING INTO A SUBTERRANEAN OIL SHALE FORMATION

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to a method of interconnecting a pair of wells; and, more particularly, interconnecting wells by means of fractures that extend through a subterranean oil shale formation.

2. Description of the Prior Art

Hydraulic fracturing is a conventional procedure that is often employed where the permeability of an earth formation is too low to permit fluid to flow into or out of the formation at a rate which is economically suitable in respect to the recovery of petroleum or other material from the earth formation. In a hydraulic fracturing operation, a fluid is confined in a region in which it is in contact with a subterranean earth formation and the pressure on the fluid is increased until a fracture is formed within the earth formation.

It is generally recognized that hydraulic fractures form along planes which are perpendicular to the least one of the three principal compressive stresses that exist along a vertical and two mutually perpendicular horizontal axes within any subterranean earth formation. At shallow depths, where the vertical stress is least, hydraulic fracturing produces a horizontal fracture. In such a situation, the fracturing occurs when the pressure applied to the fracturing fluid exceeds a pressure that is equivalent to the effective weight of the overlying earth formations by an amount sufficient to overcome the tensile and/or shear strength of the earth formation, or rock.

The pressure which is equivalent to the effective weight of the overlying earth formations is commonly referred to as the overburden pressure. It is generally equal to, or slightly less than, about 1 pound per square inch per foot of depth. The pressures required to cause a failure of a subsurface earth formation in situ is commonly referred to as the fracturing pressure and, in respect to vertical fractures, should be less than the overburden pressure unless skins present on the exposed faces of the earth formations in the well cause a temporary increase which is reflected in the pressure required to break down or initiate the fracture.

In respect to a horizontal fracture, the fracturing pressure is usually greater than the effective overburden pressure, since the overburden normally must be lifted or compressed in order to separate the layers of rock. In respect to a vertical fracture, the vertical compressive stress is greater than one or both of the compressive stresses that are perpendicular to each other within the horizontal plane. In the latter type of situation, the hydraulically induced fractures are usually vertical, and are oriented in a plane perpendicular to the weakest of the horizontal compressive stresses. In subsurface earth formations, vertical stress often exceeds the horizontal stresses and, in such situations, fractures with vertical trend will form along directions perpendicular to the smallest horizontal stresses at fracturing pressures which are less than the overburden pressure.

When a fracture is to be used in fluid production, for example, in an oil-producing operation, it may at times be advantageous to use a horizontal fracture. A horizontal fracture is preferred to a vertical fracture in respect to both the distributing of fluid over a region having a significant areal extent, and the interconnecting of a pair of wells. However, it has proven to be difficult to overcome the fracturing tendencies that are dictated by the regional tectonics and in many, if not most of the reservoirs in the United States, the least principal stress is horizontal. In such reservoirs, in order to form a horizontal fracture, it is necessary to either increase the horizontal compressive stresses or decrease the vertical compressive stress, or do both, until the vertical stress becomes the least of the three principal stresses.

Thus, it has been found that horizontal stresses are smaller than vertical stresses in many reservoirs, a condition that leads to the extension of generally parallel, nonintersecting, vertically-oriented fractures. In order to be able to extend a hydraulic fracture as a somewhat horizontal plane around the well, it is necessary to change the formation stresses so that the least principal stress is vertical.

SUMMARY OF THE INVENTION

It is an object of this invention to provide a method for interconnecting wells extending into relatively impermeable subterranean earth formations, such as oil shale formations.

It is a further object of this invention to provide a method for forming horizontal fractures in a subterranean oil shale formation that is normally susceptible to vertical fracturing.

It is a further object of this invention to change the initial preferred direction of a vertical fracture so that vertical fractures created in two wells can be interconnected.

It is a further object of this invention to provide a method for economically producing horizontal hydraulic fractures and/or connecting vertical fractures in a relatively short period of time in formations that are normally susceptible to vertical fracturing.

It is a still further object of this invention to form a horizontal fracture and/or connecting vertical fractures within an oil shale formation in a manner which connects two or more wells so that pyrolysis of the oil shale is improved.

These and other objects may be accomplished by completing at least two wells into a substantially impermeable subterranean earth formation, fracturing each well and injecting a solidifiable fluid into at least one of the fractures and maintaining the fluid at substantially a fracture-extending pressure until the fluid solidifies and plugs the fracture. At least one well in which at least one preceding fracture has been formed and plugged is then refractured and at least one newly-formed fracture is extended until the fractures intersect each other, or the wells, so that fluid may be pumped through a fracture path from one well to another.

In a preferred embodiment, horizontal fractures are formed in the oil shale at each well and extended to intersect one or more additional wells. In oil and gas operations, the benefits of the horizontal fracture may be derived without communication between wells.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a top plan schematic view of a well borehole being utilized in accordance with the teachings of my invention;

FIG. 2 is a top plan schematic view of the well borehole of FIG. 1 at a later stage in the process;

FIG. 3 is a vertical sectional view of subsurface earth formations and the well borehole of FIG. 1 and two adjacent wells which are to be interconnected;

FIG. 4 is a top plan schematic view of a pair of well boreholes being utilized in accordance with the teachings of my invention prior to changing direction of a fracture;

FIG. 5 is a top plan schematic view of one method of interconnecting the well boreholes of FIG. 4 at a later stage in the fracturing process;

FIG. 6 is a vertical sectional view, partly diagrammatic, of a preferred method of using my invention in pyrolysis of oil shale, coal, etc.; and

FIGS. 7 through 9 are vertical sectional views, partly diagrammatic, of wells being utilized in a plurality of steps for carrying out my invention when connection of wells is derived and accomplished.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The method of my invention comprises the use of the pressurized plugging of at least one well borehole fracture with an impermeable solidifiable material, such as cement, to reorient directions along which at least one refracturing will occur in order to interconnect at least a pair of well boreholes by

means of flow paths through fractures. One way of accomplishing this is to form and extend a horizontal fracture until it appears in both well boreholes. Another way is to orient and extend fractures which may be vertical (or vertical, inclined and/or horizontal) until the fractures intersect and provide a flow path between the well boreholes.

The method of accomplishing the foregoing is illustrated in FIGS. 1 through 5. A method is illustrated using pressurized fracture-plugging to form a fracture interconnecting well boreholes. Thus, in FIG. 1 an initial, vertical fracture 1 is formed extending from well borehole 2 at a pressure less than a pressure sufficient to form a horizontal fracture. Well borehole 2 extends downwardly through earth formation 4 to penetrate oil shale formation 5 (FIG. 3). Formation 5 is substantially impermeable and has a tendency to form vertical fractures. Referring now to FIG. 2, vertical fracture 1 is then filled with a fluid capable of solidifying in situ to an impermeable compression-resistant solid. This is accomplished by injecting a fluid, such as cement or a resin-forming fluid, down injection well 2, through oil shale formation 5 and into fracture 1 and allowing the solidification of the solidifiable fluid to occur at substantially the pressure required to extend fracture 1. The solidifying fluid is preferably maintained at a pressure just less than that required to inject more cementing fluid until the solidifying fluid has solidified. This may be accomplished by conventional techniques such as those used in squeeze-cementing. Any fluid which is capable of solidifying to relatively incompressible and impermeable solids also may be used and such fluids include cement, heat-sensitive organic resins, such as phenol-formaldehyde resins, epoxy resins, urea-formaldehyde resins, polyester resins, and the like.

When resins are used to plug vertical fractures and thereafter means are used to form horizontal fractures which interconnect a pattern of wells and shale oil is produced by circulating oxygen to cause combustion or by circulating a fluid heated to a temperature sufficient to pyrolyze the kerogen and decompose the heat-sensitive resin, the resin decomposition is advantageous since it exposes additional portions of oil shale to contact by the hot fluid. The tendency for the fractures to close during the decomposition of the heat-sensitive resin can be inhibited by mixing propping materials with the solidifiable material at the time it is injected into the fracture during the pressurized-plugging of the fracture.

After the pressurized-plugging of fracture 1, as illustrated in FIG. 2, a subsequent vertical fracture 3 is formed at a pressure above that required for forming fracture 1. Such refracturing is preferably repeated, with subsequent pressurized-plugging, as discussed hereinabove at successively higher pressure until a fracture is formed at a pressure sufficient to form a horizontal fracture 6 (FIG. 3). Horizontal fracture 6 may be extended, by means well known in the art combined with this invention and to be discussed further hereinbelow, into a location selected for a downhole portion of at least one adjacent well borehole, as for example, well boreholes 7 and 8 of FIG. 3.

In a preferred embodiment of this invention, at least two well boreholes 13 and 14 are drilled into oil shale formation 11 (FIG. 6) with concurrent treatment of well boreholes 13 and 14 taking place within a common depth interval in which the horizontal fracture is to be formed. Thus, in a procedure for forming intersecting fractures which may be vertical or inclined, as illustrated in FIG. 5 where vertical fractures 21*a* and 24 extend between well boreholes 13 and 14, the operations may be preferably conducted, simultaneously or sequentially, in at least two well boreholes (*i.e.*, well boreholes 13 and 14, for example). In one well, the initial vertical fracture is made. In the second well, successive fracture treatments are undertaken until the wells become interconnected.

As illustrated in FIG. 5, after forming fractures 21 and 21*a*, as shown in FIG. 4, a solidifiable fluid, as discussed hereinabove with respect to FIGS. 1 through 3, is injected into at least one of the fractures (fracture 21, for example), and the fluid is maintained at substantially a fracture-extending pressure until the fluid solidifies and plugs the fracture. At least one of the well boreholes in which at least one preceding fracture has been formed and plugged, illustrated herein as well borehole 13, is refractured and the fracture 24 so formed is extended, for example, by means well known in the art, until the fractures 21*a* and 24 intersect so that fluid may be pumped through a fracture path from one well borehole to another.

If the refracturing-solidification process is repeated a sufficient number of times, the subsurface forces may be changed so that a single horizontal fracture, which connects well boreholes 13 and 14, may be attained in an oil shale formation which initially was capable of fracturing only in the vertical direction.

Referring once again to FIG. 6, the illustrated construction of both well 13 and 14 may be similar. For example, in FIG. 6, wherein well boreholes 13 and 14 are similar to well boreholes 2, 7 and 8 of FIG. 3, each well borehole 13 and 14 has a casing 15 and 16, respectively, positioned in the borehole and sealed therein by a sealant 17 and 18, respectively, so as to maintain its location therein and prevent loss of fluids. Wells 13 and 14 may be cased only to the depth of the earth formation overburden 10. The use of uncased well boreholes is feasible whenever the native oil shale is impermeable and when it is unnecessary to control the location of the fractures.

Alternatively, and for purposes of illustration only, well boreholes 13 and 14 may be cased and perforated along part or all of the shale interval as illustrated in FIG. 6. Thus, although only a single perforation 19 and 20 is shown in well boreholes 13 and 14, respectively, obviously a plurality of such perforations may be provided. Also, in subsequent operations, to be discussed further hereinbelow, when a permeable channel formed by a horizontal fracture that extends between a pair of wells migrates upwardly through oil shale formation 11, the wells must be reentered in order to provide perforations at higher levels at which fluids will flow through the oil shale.

In the oil production operation, referring to FIG. 6, after establishing communication between well boreholes 13 and 14 as discussed hereinabove, heat exchange and pumping equipment is used to inject a first fluid down an injection well 13, through fracture 23 within oil shale formation 11 and out of production well 14 at which point circulating fluid is recovered for subsequent reinjection into well 13. In oil shale, the heat also may be generated in the oil shale by pumping oxygen to support combustion of the kerogen.

Referring now to FIG. 7, wells 13 and 14 and the adjacent oil shale formation 11 (*i.e.*, adjacent to wells 13 and 14 at perforations 19 and 20) may be notched in order to insure that a horizontal fracture 23 will be initiated at a selected depth and to provide an enlarged horizontal surface area to be acted upon by the pressure applied to the fracturing fluid. Thus, as illustrated in FIG. 7, prior to forming horizontal fracture 23, a notching tool 22 is shown disposed in well 13 adjacent perforation 19. Tool 22 is lowered into well 13 by means of a cable 22*a* of sufficient strength to raise and lower tool 22. Cable 23 may also include the necessary conduits for coupling tool 22 to a surface control unit 24. Unit 24, in conjunction with a winch or pulley 25, serves to control the operation of tool 22 in the well 13. A suitable tool for notching a subterranean oil shale formation is disclosed in a patent to Huitt et al., U.S. Pat. No. 3,050,122. Thus, tool 22 is actuated to form notch 26 in well 13 and oil shale formation 11. A similar notch 27 is illustrated in FIG. 7 as having been previously formed in well 14 and the adjacent oil shale formation 11.

The notching may precede or follow a pressurized-plugging procedure of the type discussed in connection with FIGS. 1 through 3 but, in subsurface formations that tend to fracture vertically, a horizontal fracture will not result from the fracturing operations until after the subterranean stresses have been altered by the pressurized-plugging procedure. The notch may also be created by using a drill pipe and a blade and by using sand blasting techniques which are both frequently used in oil well operations.

In forming the horizontal fracture 23, a hydraulic fracturing fluid is injected down well 13 and/or well 14 and into oil shale formation 11 at a pressure sufficient to form and extend the generally horizontal fracture 23 (FIG. 8) through oil shale formation 11. The fluid injection pressure at formation face is such that it exceeds both the effective overburden pressure and the fracturing pressure of the earth formation. The direction of the vertical fractures shown in FIG. 5 should change at pressures less than overburden pressure in most cases. The fracture 23 may be extended and/or propped by techniques well known to those skilled in the art.

Finally, a kerogen-pyrolyzing fluid is circulated down well 13 through the fracture 23 of FIG. 8 and out of well 14, thereby forming a permeable channel 29 as illustrated in FIG. 9. This fluid is heated to a temperature sufficient to pyrolyze the kerogen components of the oil shale in formation 11. Alternately the heat may be generated in situ by circulating oxygen containing fluids alone or combined with combustable materials. Conventional equipment, as illustrated in FIG. 9, may be used for heating and circulating the kerogen-pyrolyzing fluid and subsequently separating the shale oil and gas components of the fluid circulating out of production well 14 as is well known in the art.

The permeability of channel 29 may be maintained by circulating a fluid having a gaseous component therein from one borehole 13 through the fracture 29 and out the other borehole 14 while maintaining a pressure on the fluid sufficient to lift or compress the overburden by an amount sufficient to maintain an opening through which fluid can flow. The permeability of channel 29 is thus maintained by lifting the roof of the channel 29 to spatially separate the solid components of the oil shale formation 11. Such fracture may also be propped with a solid. The gaseous component of the circulating fluid is heated to a temperature sufficient to mobilize any organic components in the oil shale formation and the roof of the channel migrates up through the oil shale. The depths of the boreholes 13 and 14 through which the heated circulated fluid is flowing are adjusted to correspond with the uppermost depth along which the fluid is circulating through the permeable channel 29.

EXAMPLE

The following is an example of the economic feasibility of the method of this invention. For plane-strain in any given subterranean oil shale formation, the horizontal strain E required to increase the horizontal stresses of the formation by an amount δ p.s.i. is given by:

$$E=\frac{1-V_A}{E_A}\delta$$

For values of the Poisson ration V = 0.44 and Young's Modulus E = 1.06 × 10 p.s.i. For horizontal fractures in oil shale formation, we obtain:

$$E=0.52\times 10^{-6}\delta$$

Assuming a square pattern area of L^2 ft² per well, the width of the cement-filled vertical fractures of FIGS. 2 and 5 required to increase the horizontal stresses by an amount δ would be E L. Thus, the amount of cement required to fill the fractures (two fractures normal to each other per well pattern) is $2E\,L^2h$, where h is the height of the cement-filled fractures. Thus for a 21 gal./per ton oil shale formation, for example, the shale oil in place over the same vertical extent is:

$$\frac{(150\text{ lb./ft.}^3)L^2h(1/2\text{ bbl./ton})}{2{,}000\text{ lb./ton}}=4\times 10^{-2}L^2h\text{ bbl.}$$

From this, the amount of cement required per bbl. of shale oil in place is determined as:

$$2\times 10^{-5}\delta\text{ ft.}^3/\text{bbl.}$$

Thus, even if an increase of 1,000 p.s.i. in the horizontal stresses were required to extend hydraulic fractures in a horizontal direction, the cement requirements would be only 0.02 ft³ / bbl. The present cost of injecting cement in large quantities is about $2.00/ft³. It can then be seen that the state of stress in oil shale formations may be economically altered mechanically by the injection of cement and made conductive to the extension of horizontal fractures, all in the manner disclosed hereinabove, at a cost of only a few cents per bbl. of shale oil in situ.

I claim:

1. A method for interconnecting at least a pair of well boreholes extending into a substantially impermeable subterranean earth formation including an oil shale comprising the steps of:
   - fracturing each of said well boreholes thereby forming at least one fracture at each of said well boreholes;
   - injecting a solidifiable fluid into at least one of said fractures and maintaining the fluid at substantially a fracture-extending pressure until the fluid solidifies and plugs said fracture;
   - refracturing at least one well borehole in which at least one preceding fracture has been formed and plugged;
   - extending at least one fracture until said fractures intersect and form communication between said well boreholes through a fracture system; and
   - circulating a pyrolysis-inducing fluid from one of said well boreholes, heated to a temperature sufficient to pyrolyze kerogen components of said oil shale formation.

2. The method of claim 1 wherein the step of injecting said solidifiable fluid includes the step of injecting cement.

3. The method of claim 1 wherein the step of injecting said solidifiable fluid includes the step of filling said fracture with a heat-sensitive organic resin.

4. The method of claim 1 wherein the step of refracturing to form communication between said well boreholes includes the step of notching at least one of said well boreholes extending into said oil shale formation at a selected horizontal depth in said formation and subsequently extending such notch to obtain an intercommunicating fracture between said well boreholes.

5. The method of claim 1 including the step of recovering shale oil from the pyrolysis-inducing fluid circulating out of the other of said well boreholes.

6. The method of claim 1 wherein the step of injecting said solidifiable fluid includes the step of injecting a decomposable heat-sensitive organic resin whereby the subsequent circulation of said pyrolysis-inducing fluid decomposes the heat-sensitive resin thereby exposing additional portions of oil shale to contact by the pyrolysis-inducing fluid.