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STEAM DRIVE FOR INCOMPETENT TAR SANDS

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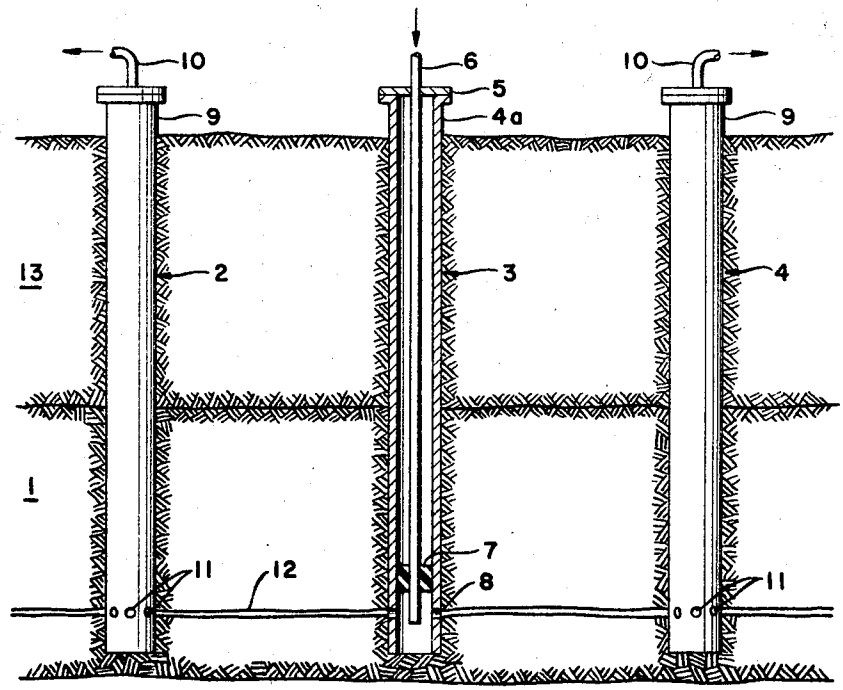


FIG. 1

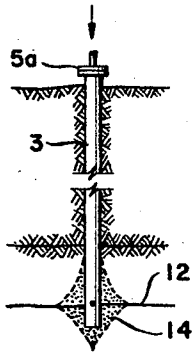


FIG. 2a

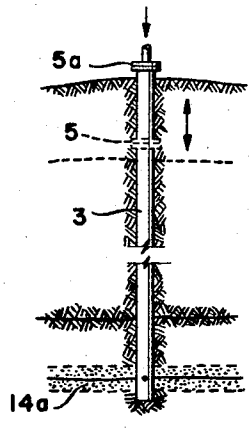


FIG. 2b

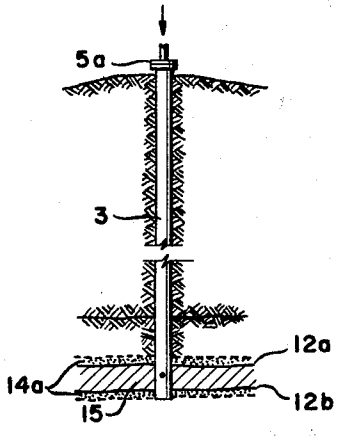


FIG. 2c

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STEAM DRIVE FOR INCOMPETENT TAR SANDS

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6 Claims. (Cl. 166—11)

This invention relates to producing a petroleum material from a subsurface reservoir that contains a viscous petroleum material, such as a tar or a viscous oil. More particularly, the invention relates to an improved steam drive process for recovering a normally viscous oil from a reservoir that is impermeable at the reservoir temperature and is incompetent at a temperature that thermally mobilizes the reservoir oil. As used herein in reference to viscous petroleum reservoirs, the term incompetent refers to a petroleum bearing earth formation, which may or may not be competent at the reservoir temperature, which tends to slump or cave into holes or fractures in the formation at a temperature at which the reservoir petroleum is thermally mobilized to an extent making it a pumpable liquid.

A previously conceived process for producing petroleum material from a reservoir that is impermeable at reservoir temperature and incompetent at a temperature that mobilizes the reservoir petroleum is described in U.S. Patent No. 3,221,813. In the patented process a fracture is extended between at least one pair of injection and production wells. A reservoir heating fluid, preferably steam, is flowed through the fracture at a pressure sufficient to separate the walls of the fracture. During the steam circulation, since the flow path between the fracture walls tends to become plugged with viscous petroleum material, higher and higher pressures must be applied in order to circulate the steam. The steam circulation is periodically interrupted in order to remove the viscous plugs and avoid the need for applying excessive pressures while the wells and flow paths are filled with pressurized steam. The viscous plugs are removed by circulating a tar-entraining liquid since the liquid can, if necessary, be injected safely at pressures that may reach the formation fracturing pressure. While steam is circulating, it removes viscous petroleum material from the fracture walls and leaves petroleum-material-depleted permeable sand. The permeable layer of sand grows vertically until it has expanded through substantially the full vertical extent of the reservoir.

Objects of the present invention include the following:

An improved process is provided for producing a thermally mobilized material from a viscous petroleum material reservoir that is substantially impermeable at reservoir temperature and incompetent at a temperature at which the reservoir petroleum is thermally mobilized.

A process is provided for heating an incompetent reservoir formation by circulating heated fluid through a horizontal fracture within the reservoir while correlating the fluid composition, the fluid flow rate, and the rate at which the fluid temperature is raised above the reservoir temperature, so that an adequate rate of flow is maintained at pressures that remain well below the fracturing pressure.

A process is provided for efficiently producing petroleum from an incompetent reservoir formation by adjusting the ratio of production wells to injection wells and the production well bottom hole pressures while circulating hot aqueous fluid. The fluid composition, flow rate and fluid heating rate are adjusted as required to maintain a pressure within the reservoir which is substantially as low as the steam pressure corresponding to the temperature selected as that to which the reservoir petroleum is heated in order to reduce its viscosity.

In general, in accordance with the present invention, petroleum is produced from a subsurface viscous petroleum reservoir which is substantially impermeable at reservoir temperature, substantially incompetent at a temperature that thermally mobilizes the reservoir petroleum and is penetrated by at least one pair of wells which are interconnected by a horizontal fracture within the reservoir. In the present process, a heated aqueous liquid is circulated through a horizontal fracture at a pressure greater than the overburden pressure while the composition of the liquid, the temperature of the liquid, and the duration of its circulation, are correlated to form a permeable layer of petroleum-depleted sand at a temperature that thermally mobilizes the reservoir petroleum. In accomplishing this, the aqueous liquid is softened by the increasing amounts required to provide an aqueous liquid that is non-scaling at the temperature to which it is heated. The heating temperature is increased to one causing a reservoir-petroleum-mobilizing temperature to be reached in the entrainment of petroleum to occur, in the circulating aqueous liquid all along the flow path between the wells. The circulation is continued until the petroleum extraction has formed a permeable layer of sand that has a temperature at which the reservoir petroleum is mobile and has a volume that can convey an adequate rate of flow at an injection pressure less than the overburden pressure. Steam is then circulated through the reservoir at a relatively low pressure and the permeable path is expanded to vertically sweep the reservoir with substantially no plugging, due to the depositing of viscous petroleum materials or scale, having been allowed to occur within the flow path.

FIGURE 1 illustrates a vertical section of a viscous petroleum reservoir that has been penetrated by wells which are suitable for use in the present invention.

FIGURES 2–A through 2–C are views illustrating the portion of the reservoir that surrounds the injection well during successive stages of heating operations in which hot fluids are circulated through the reservoir.

Referring to FIGURE 1, the drawing shows a portion of a typical pattern of injection and production wells in which an incompetent viscous petroleum reservoir formation of the type typified by the Athabasca tar sand, is penetrated by the wells **2**, **3** and **4**. Well **3** is equipped as an injection well which contains a casing string **4***a*, casing head **5**, injection tubing string **6**, packer **7**, and casing perforations **8**. Wells **2** and **4** are equipped as production wells which contain casing strings **9**, production tubing strings **10**, and casing perforations **11**. Communication between the wells is established by a horizontal fracture **12**.

In certain situations, such a fracture can be formed by injecting and pressurizing a fluid that is pumped through tubing string **6** and perforations **8**. When the pressure becomes sufficient to form a horizontal fracture, such as fracture **12**, and separate the fracture walls by lifting the overburden **13**, the fluid flows on through the fracture and into the perforations **11** and the production tubing strings **10** of the production wells **2** and **4**. If a fluid which is so circulated is heated to a temperature that mobilizes the reservoir petroleum material, the mobilized petroleum tends to become entrained in and extracted by the circulating fluid. As long as the entrained petroleum stays mobile until it reaches the production well, the flow path remains unplugged and tends to expand as more petroleum is extracted to leave more petroleum-depleted permeable sand.

A steam such as a dry or low quality steam is a particularly suitable heated fluid to be circulated through such a reservoir. However, as is discussed in U.S. Patent No. 3,221,813, it is necessary to periodically interrupt the steam circulation in order to effect a liquid extraction of

petroleum materials that have cooled and form viscous plugs within the flow path that interconnects the wells.

It has now been discovered that such a plugging of such a flow path can be substantially completely avoided. In order to do this, the initial portion of the heating operation is conducted by circulating hot water through the reservoir. At this stage the water-circulating heating process is advantageous. However, such a heating procedure would become too expensive if it were to be utilized to heat all of the swept zone within the reservoir interval. The hot water heating is accomplished by heating the water at a surface location and circulating it through the reservoir at a rate sufficient to transport heat from the surface location to the openings into the production well. This requires the maintenance of a flow rate that is at least about $\frac{1}{10}$ barrel per minute, in a relatively shallow reservoir in which there is a relatively low heat loss in the injection tubing string. Higher rates are required in respect to deeper reservoirs or situations involving higher heat losses.

We have further discovered that the water which is used must be softened by the increasing amounts required to yield an aqueous liquid that is non-scaling at the temperature to which it is heated.

The heating and circulating of hot water are continued until the fluid that enters the production well is at least hot enough to thermally mobilize the reservoir petroleum. They are preferably continued until the temperature of fluid entering the production well is sufficient to reduce the viscosity of the reservoir petroleum material to less than about 50 cp. When, or relatively soon after, such a temperature has been attained, the fluid being circulated through the reservoir is converted from liquid to steam.

FIGURE 2–A shows the region around the injection well **3** during an early stage of heating the reservoir by injecting steam into fracture **12**. In such an operation the steam tends to condense and yield most of its heat near the well. This is indicated by dotted region **14**, in which the variation in vertical distance away from fracture **12** represents the variation in the temperature with horizontal distance away from well **3**. As the steam leaves the well, the reservoir petroleum which is thermally mobilized and swept along with the flow of steam moves from a hot region into a region that is relatively cool. The cooling petroleum tends to form a viscous plug before it reaches the production well.

FIGURES 2–B shows the region around injection well **3** during an early stage of heating the reservoir formation by the present process. In such an operation, heated aqueous liquid is circulated between the injection and production wells at a flow rate such that heat is transported from the surface located heater to the openings into the production well. This causes the heat to be distributed substantially uniformly along the fracture in the manner indicated in section by the dotted region **14***a*.

Such a heating of a layer of subsurface earth formation causes a lifting of the overburden, as is indicated by the dotted and solid representations **5** and and **5***a* of the wellhead **5**. However, in the present process, such a lifting of the overburden causes no significant increase in the pressure required to separate the walls of fracture **12** and circulate the liquid through the reservoir. Such injection and production wells are usually separated by significant distances, and even where they are separated by as little as 25 feet, such a heated zone would have an area of nearly 2000 square ft. The force required to bend the overlying strata by an amount sufficient to accommodate the lifting of the overburden would be insignificant in respect to the force produced by applying the overburden pressure to an area of more than 2000 square feet.

FIGURE 2–C shows the region around injection well **3** during a later stage of heating the reservoir formation by the present process. In this stage the fracture walls have been moved apart as indicated at **12***a* and **12***b*. The space between the fracture walls is occupied by petroleum-depleted permeable sand **15**. A general characteristic of viscous petroleum reservoirs that are substantially impermeable at reservoir temperature and incompetent at a temperature that mobilizes the reservoir petroleum is that, when such a reservoir formation is depleted of petroleum, it becomes a permeable sand.

In operating the present process, as soon as the fracture walls have become heated to a temperature that mobilizes the reservoir petroleum, the mobilized petroleum begins to be entrained in and extracted by the circulating hot water. Since the temperature is uniform along substantially the entire distance between the injection and production wells, the entrained petroleum encounters no cool zone in which it can become a viscous plug.

After the flow path through the reservoir has been heated to a temperature that mobilizes the reservoir petroleum, the circulating heated fluid is converted from liquid to steam.

When the volume of petroleum-depleted permeable sand is sufficient to convey fluid at an adequate rate of flow at an injection pressure of less than the overburden pressure, the injection pressure is preferably reduced to such a lower pressure. This allows the weight of the overburden to rest on the layer of permeable sand. Since this sand differs from the other portion of the reservoir sand only in the absence of petroleum, it does not tend to become embedded in the walls of the fracture. As the fracture walls are converted to the permeable sand, the fracture is, in effect, replaced by a permeable path that consists of a layer of petroleum-depleted permeable sand.

Steam is preferably circulated through the permeable path at substantially the steam pressure corresponding to a temperature at which the reservoir petroleum is thermally mobilized. A back pressure within the production wells is desirable only if necessary in order to maintain a steam pressure corresponding to a selected temperature. In general, the flow resistance within the permeable path through the reservoir provides sufficient back pressure when the flow rate is relatively high. It is generally preferable to circulate the steam at a relatively high rate at relatively low pressure by (1) providing at least about four production wells that are responsive to each injection well (2) injecting the steam at a rate such that at least some live steam is transported through the reservoir and into substantially all of the production wells and (3) maintaining a low bottom hole pressure in each production well by pumping fluid out of the well at a rate sufficient to produce at least some live steam. In reservoir formations that are similar the Athabasca tar sand, a particularly suitable steam injection rate is a rate in the order of about 10 to 20 tons per acre per day.

In heating and circulating an aqueous liquid in the present process, the aqueous liquid can comprise substantially any liquid that is inert at the temperature to which it is heated. Pure water, brine, or brackish water, can be used. However, it is essential that the aqueous liquid which is used be softened as required to provide a liquid that is substantially non-scaling at the temperature to which it is heated. Omitting such a softening allows scale to form in the tubing string and the fracture and/or the layer of oil-depleted permeable sand that is being formed within the fracture. Such a scaling decreases the permeability and, as the permeability is decreased, higher pressures are required to maintain an adequate rate of flow. Such effects accumulate until the injection pressure reaches a fracturing pressure and forms a new fracture, which opens a new flow path that bypasses portions of the reservoir that were previously heated. The water softening procedure can utilize substantially any of the precipitation, ion-exchange, chelation, or the like techniques that are known to those skilled in the art for keeping the alkaline earth metal ions from precipitating to form scale at elevated temperatures. A particularly suitable water softening technique, which is designed to prevent scaling at the temperatures used in numerous thermal processes for producing oil, is described in U.S. Patent No. 3,193,009.

When a temperature that exceeds 212° F. has been attained within the fracture through which heated aqueous liquid is circulated in the present process, the fluid being circulated through the fracture is preferably converted from a liquid to steam. Such a conversion is preferably initiated as soon as the fracture walls have been heated to a temperature above 212° F. that reduces the viscosity of the reservoir petroleum to a relatively low value, such as less than about 50 cp. The rate at which the conversion is affected is critical in the sense that it should be slow enough to avoid any localized cool spots within the flow path that interconnects injection and production wells. During the conversion, the steam temperature is preferably kept equal to that of the hot water, with the changeover being gradual, rather than incremental.

The conversion from hot water to steam is preferably affected by increasing the residence time of the aqueous fluid in the heater. This causes increasing proporitons of the fluid to be converted from liquid to steam at the same temperature and pressure that were being imparted to the heated aqueous liquid. The rate at which the liquid is converted to steam is preferably monitored by determining the temperature of fluid entering the production well and keeping the rate low enough so that substantially no decrease occurs in that temperature. Such determinations can be made conveniently with conventional downhole, or surface located, temperature measuring devices. Where the surface located devices are used, it is, of course, preferable to calibrate for the changes in temperature that occur during the passages through the well.

The conversion from hot water to steam can either precede or follow the reduction of the injection pressure to less than overburden pressure. It is generally preferable to reduce the pressure while circulating hot water in order to allow the weight of the overburden to settle onto the layer of permeable petroleum depleted sand before converting from hot water to steam. This avoids the need for a boiler capacity sufficient to generate steam at a relatively high rate at a pressure greater than the overburden pressure. In addition, when the pressure is lowered before initiating the conversion, the pressure reduction and the conversion from water to steam is generally smoother and leads to an earlier production of significant amounts of oil.

In various viscous petroleum reservoirs which are substantially impermeable at reservoir temperature and incompetent at a temperature that thermally mobilizes the reservoir petroleum, horizontal fractures form when conventional fracturing procedures are employed. In reservoirs which are normally biased toward horizontal fracturing the present oil recovery process can be initiated by opening a pair of wells into the reservoir and interconnecting them via a horizontal fracture that is formed by means of known procedures. In reservoirs in which the regional tectonics are such that only vertical fractures are formed when conventional fracturing procedures are employed, or in reservoirs in which the fracturing tendencies are unknown or are likely to produce vertical fractures, the present oil recovery process is preferably initiated by: opening a pair of boreholes into the reservoir, thermally biasing the reservoir to form a horizontal fracture, and then interconnecting the wells by forming a horizontal fracture within the thermally biased reservoir. In thermally biasing a reservoir to form a horizontal fracture that extends away from a well, the reservoir is first vertically fractured at the reservoir temperature. Liquid is then pumped into the fracture at a rate adapted to transport heat from a surface location to the fracture. The inflowing liquid is heated to temperatures that are made increasingly greater than the reservoir temperature while increasing the injection pressure as required to maintain the flow rate. The liquid injection is continued, while the temperature and pressure are so increased, until a horizontal fracture is formed. Such a thermal biasing procedure is described in greater detail in the co-pending application of C. S. Matthews, P. Van Meurs and C. W. Volek, Ser. No. 578,533, filed Sept. 12, 1966.

Example I.—Oil production

Field tests in the Athabasca tar sand have demonstrated that commercial oil production can be obtained by circulating steam through such a tar sand. In the tests, a permeable path was formed by extending a horizontal fracture between a pair of wells. During the circulation of steam, recurrent plugging of the flow path necessitated interruptions of the steam circulation while a tar entraining liquid was circulated in order to remove the plugs. The flow path through which the steam was circulated expanded vertically and the vertical sweep efficiency of the oil production operation was good.

A linear model was prepared to simulate a portion of a reservoir, having the characteristics of an Athabasca tar sand, between rows of wells for injecting and producing fluids. The model was filled with inert granular material from which water was displaced by oil until only a residual water saturation was left in the granular material. A horizontal fracture that interconnected a pair of wells was mechanically opened at the bottom of the model reservoir.

Scaled experiments with the model demonstrated that, in the modeled reservoir, as in the field, plugging occurred when dry steam or low quality steam was circulated through the fracture before heat had been imparted to an extensive region within the reservoir. In both the model reservoir and the field reservoir the occurrence of plugging was indicated by simultaneous occurrences of a pressure increase while fluid was being injected at constant rate and a decrease in the temperature of the fluid that entered the production well. Such events indicate that communication between the injection and production wells is being lost. It was observed, in both the model and the field reservoir, that such plugging materials could be removed by interrupting the circulation of steam and injecting a slug of hot liquid tar-entraining material while applying sufficient pressure to force a circulation of the tar-entraining material through the flow path from the injection well to the productoin well.

A series of additional tests with the model reservoir formation indicated the suitability of two different methods for preventing plugging. In the first, the heating was initiated by circulating hot water until the temperature of the production well was raised to such a level that the tar became mobile. Then low-quality steam injection was started. Both during hot-water injection and during low-quality steam injection, the B.t.u. injection rate was kept constant at the maximum capacity of the boiler. During the next phase of the process the quality of the injected steam was raised, again at constant heat injection rate, in such a manner that the temperature of the production well did not decrease. When the temperature of the production well reached steam temperature the fracture was gradually closed mechanically, starting at the production side. In the field the fracture can be closed by decreasing the back-pressure on the production well. The fracture will be completely closed when the injection pressure has dropped below overburden pressure.

In the second method, as in the first, injection was started with hot water until the temperature of the production well was high enough to mobilize the tar. Then the fracture was gradually closed while the injection of hot water was continued. The closing of the fracture was carried out at such a rate that the temperature of the production well did not decrease. When complete closure of the fracture was obtained, a changeover was made from the injection of hot water to steam of a gradually increasing quality. Again the steam quality was raised in such a manner that the temperature of the production well did not decrease.

Comparison of the two methods showed that the second

method, in which the fracture was closed before steam injection was started, worked smoother and showed an earlier oil production response than the first, in which the fracture was heated with steam before being closed.

Example II.—Fluid composition control

The importance of softening the aqueous liquid that is heated and circulated through a horizontal fracture and the feasibility of slowly converting the circulating fluid from hot aqueous liquid to steam has been demonstrated in field tests. A pattern of injection and production wells was completed in a shallow layer of Missouri tar sand and an interconnecting horizontal fracture was extended from the injection well to the production wells at a depth of 300 feet. The fracturing pressure was in the range of 800–1000 p.s.i., and cold water could be circulated through the fracture at about 5 bbl./minute at a bottom hole pressure of 410 p.s.i.g.

The water used was obtained from a nearby source well and was heated by mixing it with steam. As the so heated water was circulated through the fracture, the pressure required to maintain the circulation rate soon began to rise. Remedial treatments, including the propping of the fracture, failed to eliminate the need for increasing the pressure in order to maintain the circulation rate. It was later discovered that the scale-depositing tendency of the water increased with temperature, and the increase in the pressure requirement was due to the tubing string and fracture becoming plugged with scale.

The wells were acidized to reduce the plugging effects of the scale deposit in respect to circulating a liquid through the fracture. The same water was softened by process of the type described in U.S. Patent No. 3,193,409 to the extent required to provide a liquid that deposited no scale at the temperature to which it was heated. The initial portions of softened water were heated in the manner described above to a temperature estimated to have remained in the fracture and the temperature of the circulating water was increased at a rate of about 50° per day. The heating and circulating were continued until water was being circulated at 475° F. at a pressure well below the formation fracturing pressure.

While continuing to circulate the hot water at 475° F., the rate at which the water flowed through the heater and fracture was gradually throttled back to half the initial rate. The rate reduction was affected by over about a three-day period, so that it caused a longer residence time in the heater and without causing any significant change in the temperature or pressure of the fluid injected into the fracture. Thus, the circulating fluid was gradually converted from liquid to steam. The quality of the steam was then gradually increased to a steam quality of about 60 percent. This conversion from liquid to steam caused no decrease in the temperature of the fluid that entered a monitor well 25 feet from the injection well.

We claim as our invention:

1. A process for producing petroleum from a viscous petroleum reservoir that is substantially impermeable at reservoir temperature, is substantially incompetent at a temperature that thermally mobilizes the reservoir petroleum and is penetrated by at least one pair of wells that are interconnected by a horizontal fracture extending through the reservoir, which process comprises:

(a) heating aqueous liquid at a surface location and circulating the heated liquid through the fracture between said pair of wells while maintaining a back pressure that at least substantially equals the overburden pressure and an injection pressure that causes flow at a rate adequate for transferring heat from the surface location to the openings into the production well;

(b) increasing the temperature of the circulating heated aqueous liquid until fluid flowing into the production well has a temperature that thermally mobilizes the reservoir petroleum while increasing the softness of the aqueous liquid to the increasing extent required to provide a liquid that is nonscaling at the temperature to which the liquid is being heated;

(c) forming a permeable path within the reservoir by entraining the thermally mobilized reservoir petroleum in the circulating heated aqueous liquid and thus converting a portion of the reservoir to a layer of petroleum-depleted permeable sand;

(d) reducing the pressure within the reservoir to less than overburden pressure and circulating steam through the reservoir at a temperature at which said reservoir petroleum is mobilized and entrained;

(e) recovering said petroleum from fluid that has circulated through the reservoir.

2. The process of claim 1 wherein:

(a) the rate at which fluid is circulated through the reservoir is at least greater than 1/10 bbl./minute; and

(b) the temperature to which the circulating fluid is heated is increased to at least a temperature at which the reservoir petroleum viscosity is less than 50 cp.

3. The process of claim 1 wherein:

(a) the circulating of heated aqueous liquid is continued during and after said reduction of the pressure within the reservoir to less than overburden pressure; and

(b) the conversion of the circulating fluid from liquid to steam is effected so gradually that no significant temperature reduction occurs in the fluid that enters the production well.

4. The process of claim 1 wherein:

(a) the reservoir is an incompetent tar sand; and

(b) the rate at which steam is circulated through the permeable path within the reservoir is in the order of 10 to 20 tons per acre per day.

5. The process of claim 1 wherein:

(a) the reservoir is one in which fractures that are formed at reservoir temperature are vertical fractures;

(b) the reservoir is intially vertically fractured at reservoir temperature; and

(c) aqueous liquid is injected into the fracture formed at reservoir temperature while relatively slowly increasing the temperature of the injected aqueous liquid and increasing the injection pressure as required in order to maintain a selected rate of flow until the temperature and injection pressure have increased to magnitudes at which the vertical fracture is closed by the thermal expansion of its walls and a horizontal fracture is formed and extended until it interconnects a pair of wells.

6. A process for producing petroleum from a viscous petroleum reservoir that is substantially impermeable at reservoir temperature, is substantially incompetent at a temperature that thermally mobilizes the reservoir petroleum and is penetrated by at least one pair of wells that are interconnected by a horizontal fracture extending through the reservoir, which process comprises:

(a) heating aqueous liquid at a surface location and circulating the heated liquid through the fracture between said pair of wells while maintaining a back pressure high enough to provide a pressure in the fracture that is sufficient to separate the walls of the fracture so as to cause flow at a rate adequate for transferring heat from the surface location to the openings into the production well;

(b) increasing the temperature of the circulating heated aqueous liquid until fluid flowing into the production well has a temperature that thermally mobilizes the reservoir petroleum while increasing the softness of the aqueous liquid to the increasing extent required to provide a liquid that is nonscaling at the temperature to which the liquid is being heated;

(c) forming a permeable path within the reservoir by entraining the thermally mobilized reservoir petrole-

um in the circulating heated aqueous liquid and thus converting a portion of the reservoir to a layer of petroleum-depleted permeable sand;

(d) reducing the pressure within the reservoir to less than overburden pressure and circulating steam through the reservoir at a temperature at which said reservoir petroleum is mobilized and entrained; and

(e) recovering said petroleum from fluid that has circulated through the reservoir.

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