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**METHOD OF PROLONGING THE USEFULNESS
OF PRODUCTION WELLS IN THERMAL-RECOVERY PROCEDURES**

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This invention relates to prolonging the useful life of production wells employed in thermal recovery of petroleum and increasing the quantities of valuable fluids obtainable therefrom.

"Thermal recovery" is a term used to describe methods in which combustion is maintained in a petroleum-bearing stratum by injecting air or another oxygen-containing mixture of gases into the stratum through one or more injection wells while petroleum (or petroleum modified by cracking and oxidation reactions) is withdrawn from one or more production wells.

In such methods, a combustion front is created in the formation, and it progresses from the injection well or wells toward the production well or wells. Hot, gaseous combustion products move through the formation ahead of the combustion front. Consequently, the viscosity of the oil is decreased and the reservoir pressure is increased. As a result, it is possible to recover petroleum which otherwise would be impossible to obtain.

If the method is continued, the combustion front must eventually reach a production well. Heretofore it has been supposed that when this occurs the usefulness of the production well is ended. It has been believed that when the temperature and the composition of the mixture of fluids withdrawn from a production well indicate that the combustion front has reached that well, the well must soon be plugged and abandoned or (if the pattern of the field permits) converted into an injection well.

I have discovered, however, that the usefulness of a production well can be prolonged beyond that time by cooling the bottom of the well to a temperature lower than the ignition point of the fluids therein. When this is done, the well has an extended period of productivity. During the extension of the well's useful life, the gases produced by the well include free oxygen. From this I conclude that the loss in petroleum yield and the destructive temperatures which have been associated with the arrival of the combustion front at a well have been to a considerable extent caused by combustion in the well itself rather than in the formation.

The reduction in temperature is achieved by circulating a coolant fluid through the well, preferably by injecting it into the annulus between the casing and the tubing. The most efficient cooling is obtained when the coolant is a vaporizable liquid having considerable heat of vaporization at the well-bottom pressure and temperature and when it is injected at such a rate that the bottom of the well contains the coolant in both the liquid and vapor states.

In a high-pressure well, however, it may be desirable to cool the well fluids to a temperature lower than the boiling point of the coolant liquid at the existing pressure. This may be achieved by injecting the coolant at a rate greater than that which permits boiling to occur in the bottom of the well; such procedure sacrifices the efficiency of cooling by vaporization but yields a greater total cooling effect. The reason for the additional cooling may be merely that the coolant boils at a temperature high enough to be damaging to well equipment, or it may be that the boiling point of the coolant is greater than the ignition temperature of the petroleum. The latter can occur because the boiling point of a liquid increases with increasing pressure while the ignition temperature of

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petroleum decreases. At pressures in the neighborhood of 400 pounds per square inch, or even as low as 300 pounds per square inch in the case of some kinds of petroleum, the boiling point of water becomes greater than the ignition point of the oil.

Ordinarily water is by far the most effective, available, and economical coolant. Even in arid regions water for purposes of the herein-disclosed method is obtainable from the condensers and storage tanks in which fluids from the production wells are handled. No unusual precaution to prevent loss of water derived from the wells is required, because lost water is replaced by new water from the oil-bearing formation, consisting of both connate water and water formed as a combustion product.

Other coolants may be employed. Diethylene glycol and similar polyhydric alcohols are costly but may be recirculated virtually without loss because of their low volatility and their insolubility in petroleum. They have the advantage of permitting control through a wider range of pressure-temperature conditions than is possible when water is the coolant. In a high-pressure well wherein the boiling point of water is greater than the ignition point of petroleum, it may be desirable to replace a portion of the water with another fluid having the ability to reduce the average boiling point of the coolant, to increase the ignition point of petroleum, or both. For example, a pressure condensate prepared from the gases and vapors produced by the well, which includes water, carbon dioxide, and lower hydrocarbons, may be employed. The fact that the lower hydrocarbons are combustible does not preclude their use for this purpose.

In a production well of a field being operated by a thermal-recovery method, increases in the temperature of the well fluids begin to be observed at some time during the procedure. The rate of temperature increase, which is small at first, becomes greater as the combustion front approaches the well more closely. When the bottom-hole temperature of a well reaches a point about 100° F. more than the original temperature of the formation of a temperature of about 200° F., whichever is greater, it may be taken as an indication that the combustion front has approached the well so closely that cooling should be initiated. If necessary, the bottom-hole temperature can be roughly estimated from the surface temperature of the well fluids by the use of an empirical correction applicable to the particular field which is being operated.

If the cooling is started at this point, the volume of water needed to prevent further immediate increase of well-bottom temperature is initially small. But as the combustion front approaches more closely, it is necessary to inject water in greater volume. Eventually the temperature must be permitted to increase to avoid the use of so much water that the capacity of the well tubing to conduct valuable fluids to the surface is seriously interfered with. Thereafter, the flow of water is controlled so that there is enough to maintain a liquid aqueous phase in the bottom of the well (as indicated by measurements of bottom-hole temperature and pressure or as deduced from the temperature and/or composition of the fluids obtained from the well) but not enough to overload the capacity of the well to conduct fluids to the surface to such an extent that the production of oil and gas is seriously impeded.

If the well bottom is successfully kept at a temperature lower than the ignition point of the petroleum, when the combustion front actually reaches the well free oxygen begins to appear in the gases withdrawn. Observation of the amount of free oxygen serves as a convenient guide to the amount of water required to be circulated. If the proportion of oxygen falls off sharply, it is an indication that combustion is occurring in the well and that

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the flow of water should be increased. It is possible, however, for the oxygen content of the gases to diminish for other reasons. Therefore, if augmenting the flow of water does not restore the oxygen content of the gases, it is preferable to study temperature readings and other observable factors with care to ascertain what is occurring in the well and in the adjacent formation.

Whether cooling is employed or not, corrosion in thermal-recovery wells is a serious problem. While reduced temperature in itself has a beneficial effect upon corrosion, the presence of free oxygen, saturated steam, and liquid water has an adverse effect. Corrosion difficulties may be overcome to an adequate extent by using resistant materials such as stainless steel for the most seriously exposed well equipment, especially the liner.

In an experimental thermal-recovery program in a California oil sand at a depth of about 700 feet, one of the production wells failed after having been operated at high temperatures for about 47 days. A new liner and tubing were successfully installed, and production of the well was resumed with injection of water into the annulus at the rate of 57 barrels per day.

Temperature of the gases issuing from the oil-and-gas separator was observed, and was found to average 190° F. during a two-hour period before the circulation of water was started. The average temperature during the two-hour period after the use of water was commenced was 165° F. At this time the well was producing at the rate of 83 barrels per day of oil, 48 barrels per day of water, and 520,000 standard cubic feet (520 M s.c.f.) per day of gases. The gases contained 0.2% of free oxygen.

Six days later water was being injected at the rate of 55 b./d. and the surface temperature of the gas stream was 167° F. Circulation of water was interrupted for a three-hour period during which the average surface temperature of the gas stream was observed to be 217° F. Injection of 55 b./d. of water was then resumed, with the result that the average gas temperature fell to 170° F. At this time the well was producing at the rate of 85 b./d. oil, 64 b./d. water, and 438 M s.c.f./d. gases.

Thirteen days later a series of observations of the gas composition was commenced. On the first day, with a water-injection rate of 28 b./d., the oxygen content of the gas was 8.4%. On the second day, with the same water rate, the oxygen content was 9.1%. On the third day circulation of water was interrupted with the result that the oxygen content fell to 0.2% and was then resumed at the rate of 56 b./d., causing the oxygen content to increase to 8.9%. Injection of 56 b./d. of water was continued, and the oxygen content on the fourth and fifth days was 5.1% and 9.2%, respectively.

Successful operation of the well with cooling was continued, with the free oxygen content of the gases gradually increasing as greater amounts of unconsumed oxygen from the air-injection well reached the production well. Fifty-one days after the injection of water was first employed, the oxygen content of the gases was 13.5%.

The well produced as described for a total of eighty days without trouble, and then the tubing became plugged. It was attempted to recover the well fluids through the annulus while pumping water down the tubing, but the water did not reach bottom because of a hole in the tubing. Flow was then switched back to normal, but it was still impossible to achieve circulation of water through the well bottom. After two days of attempted production without effective cooling, as indicated by absence of free oxygen in the gases and well-head temperatures of 330° F., the well was shut in, killed and pulled.

It was found that the inner casing had parted about half-way down the well. It is believed that this was an effect of the extreme temperatures which caused thermal expansion of the casing and pushed the top of the casing

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upwardly through its slips and thus resulted in parting of the casing when it was subsequently cooled.

The well was then plugged with cement and abandoned. At this time loss of pressure was observed at other wells in the test area, indicating that the plugging was unsuccessful in preventing the loss of gas (and presumably other fluids) from the oil sand into other permeable strata. It is thought that this failure was the result of damage by heat to the outer casing or to its water shut-off located just above the producing interval.

A substitute well was drilled 25 feet from the original well, in the direction directly opposite to that of the injection well. The substitute well was completed with a stainless steel liner, and was operated from the beginning with bottom-hole temperatures less than or equal to the temperature of saturated steam at the existing pressure.

When the well was put on production injection of water at the rate of 26 barrels per day was commenced. During the following four days the rate of water injection was increased rapidly to 70 barrels per day, and through the following month injection rates of 250-270 barrels per day were maintained. During the remainder of the test period the quantity of water was decreased and at the end it was about 50 barrels per day.

Core samples taken in the drilling of the substitute well indicated that a portion of the producing interval had been burned and, therefore, that the combustion front had reached that point. Nevertheless, for the first five months of operation, substantial quantities of free oxygen were seldom observed in the gases from the well, in spite of consistently high temperatures at the bottom. The combustion front must have been in the vicinity of the new well, but it is apparent that its progress was being interfered with by the loss of gases through the abandoned well.

Because the loss of fluids in the abandoned well had an adverse effect upon operation of the test area as a whole, the well was reentered and plugged more effectively. Thereafter, free oxygen began to appear in the effluent from the substitute well and increased in amount through a period of two and a half months, at the end of which time the experimental thermal-recovery program was terminated. Production from this well was good, ranging from 320 b./d. of oil at the beginning of its life down to about 80 b./d. at the end of the program. No operational difficulties were encountered and no down-the-hole work of any kind was required.

Previous to the events set forth above, another of the production wells in the test area had been destroyed by events associated with the arrival of the combustion front, including a blow-out during which an estimated 1500 barrels of oil were lost. This well had then been plugged with cement and there was no production from its sector for a period of six months, at the end of which time a substitute well, placed in the same manner as the substitute well described above, was completed. Core samples indicated that there had been no burning in the oil sand at the new site but that the oil content was only about half of the original. This substitute well, like the other, was completed with a stainless steel liner and water was injected into the annulus from the beginning, in amount sufficient to keep the bottom-hole temperature from rising above that of saturated steam.

During the first month this well was pumped, with production ranging from about 20 to about 40 b./d. Then the well started flowing freely at a rate of 140 b./d. of oil. For the following seven months the well functioned satisfactorily, although production subsided and has fluctuating between 20 and 40 b./d. at the end of the experimental program. Definite arrival of the combustion front, as indicated by appearance of substantial quantities of free oxygen in the well fluids, occurred about two and a half months after the well went on production.

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After an initial period of relatively low-temperature operation, cooling water was employed in this well at rates ranging from 50 to 200 barrels per day, depending upon well conditions. On one day experimental variation of the water rate was tried, with the following results:

Oil Rate, bbls./day	Gas Rate, M.s.c.f./day	Bottom- hole Temp., ° F.	Water Rate, bbls./day
92	420	380	10
92	420	305	60
92	420	281	180

The casing-head pressure was 89 pounds per square inch gauge, at which the saturated steam temperature is 330° F. The data indicate that a water rate of 10 bbls. per day was insufficient to maintain a liquid aqueous phase at bottom-hole conditions, that a water rate of 60 bbls. per day was somewhat in excess of the minimum requirement, and that tripling the water rate from 60 to 180 bbls. per day resulted in a minor decrease in temperature of 24° F. It is also worthy of note that even when water was injected at the rate of 180 bbls. per day, there was no observable decrease in the rates of production of oil and gas as a result of overloading the capacity of the well to conduct fluids.

During the period before free oxygen is available at the bottom of a well, circulation of water is not needed for the purpose of preventing combustion. It might be thought that its use should be avoided then because it occupies space in the well, increases the viscosity of the heavy petroleum for which thermal recovery is most suitable, and aggravates emulsion problems. However, experience in the first well discussed in the foregoing, as compared with experience in the replacement wells, indicates that preliminary cooling is desirable for reducing damage to metallic and cementitious materials employed in the well. Beginning the cooling at the time set forth above, i.e., when the bottom-hole temperature reaches 200° F. or a point 100° F. greater than the original formation temperature, provides reasonable assurance that avoidable damage to existing well equipment will not occur.

I claim as my invention:

1. The method of prolonging the useful life of a production well employed to withdraw petroleum fluids from an oil sand being operated by a procedure wherein combustion of combustible material in said oil sand has been initiated and is maintained by injection of an oxygen-bearing gas into said oil sand through an injection well and petroleum fluids enter said production well from said oil sand which comprises: circulating a coolant fluid through said production well in contact with said petroleum fluids at least when the temperature of the fluids in the bottom of said production well reaches the greater of the two temperatures 200° F. and the temperature 100° F. more than the original temperature of the oil sand, and controlling the volume of flow of said coolant fluid so that the temperature in said production well bottom remains less than the ignition point of the combustible fluids therein.

2. The method of prolonging the useful life of a production well employed to withdraw petroleum fluids from an oil sand being operated by a procedure wherein combustion of combustible material in said oil sand has been initiated and is maintained by injection of an oxygen-bearing gas into said oil sand through an injection well and petroleum fluids enter said production well from said oil sand, the pressure in said production well being less than the pressure at which the boiling point of water equals the ignition temperature of combustible fluids in said well which comprises: circulating water through said

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production well in contact with said petroleum fluids at a rate of flow such that the temperature of the production well bottom is maintained at about the temperature of saturated steam under the existing pressure.

3. The method of prolonging the useful life of a production well employed to withdraw petroleum fluids from an oil sand being operated by a procedure wherein combustion of combustible material in said oil sand has been initiated and is maintained by injection of an oxygen-bearing gas into said oil sand through an injection well and petroleum fluids enter said production well from said oil sand which comprises: circulating a coolant fluid through said production well in contact with said petroleum fluids at a rate sufficient to maintain the bottom of said production well at a temperature below the boiling point of said coolant fluid at the pressure existing at the bottom of said production well, the temperature of the oil sand in the vicinity of said production well bottom being such that the production well bottom temperature becomes greater than the ignition point of the combustible fluids therein when said circulation of coolant is not employed.

4. The method of claim 3 wherein said coolant fluid is water.

5. The method of claim 3 wherein said coolant fluid is diethylene glycol.

6. The method of prolonging the useful life of a production well employed to withdraw petroleum fluids from an oil sand being operated by a procedure wherein combustion of combustible material in said oil sand has been initiated and is maintained by injection of an oxygen-bearing gas into said oil sand through an injection well and petroleum fluids enter said production well from said oil sand which comprises: removing said petroleum fluids from said production well along with water native to said oil sand and formed by combustion in said oil sand which water accompanies said petroleum fluids entering said production well, separating said water from said petroleum fluids, circulating said separated water through said production well in contact with said petroleum fluids in said production well in an amount sufficient to maintain the bottom of said production well at a temperature less than the ignition point of the combustible fluids therein, the temperature of the oil sand in the vicinity of said production well bottom being such that the production well bottom temperature becomes greater than said ignition point when said circulation of coolant is not employed.

7. The method of prolonging the useful life of a production well employed to withdraw petroleum fluids from an oil sand being operated by a procedure wherein combustion of combustible material in said oil sand has been initiated and is maintained by injection of an oxygen-bearing gas into said oil sand through an injection well and petroleum fluids including combustible fluids having an ignition point less than the boiling point of water enter said production well from said oil sand which comprises: removing said petroleum fluids from said production well, passing said petroleum fluids to a separating means, removing a pressure condensate including water, carbon dioxide, and lower hydrocarbons from said petroleum fluids in said separating means, passing said pressure condensate to said production well, and circulating said pressure condensate through said production well in contact with said petroleum fluids in said production well in an amount sufficient to maintain the bottom of said production well at a temperature less than the ignition point of the combustible fluids therein, the temperature of the oil sand in the vicinity of said production well bottom being such that the production well bottom temperature becomes greater than the ignition point of the combustible fluids therein when circulation of said pressure condensate is not employed.

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