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M. L. SLUSSER ET AL
IN SITU RETORTING OF OIL SHALE BY
TRANSIENT STATE FLUID FLOWS

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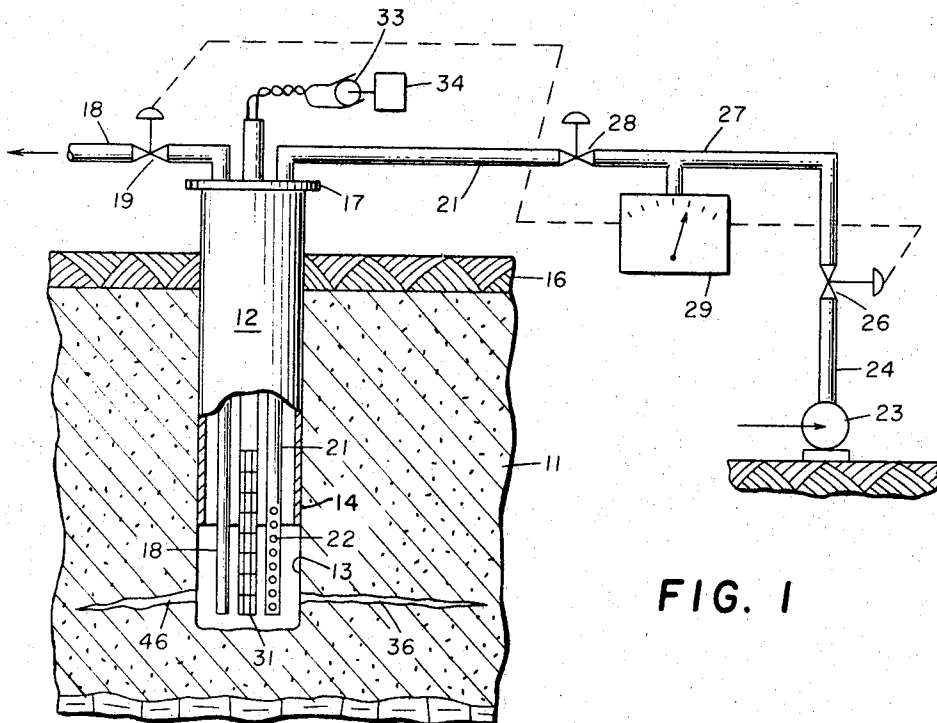
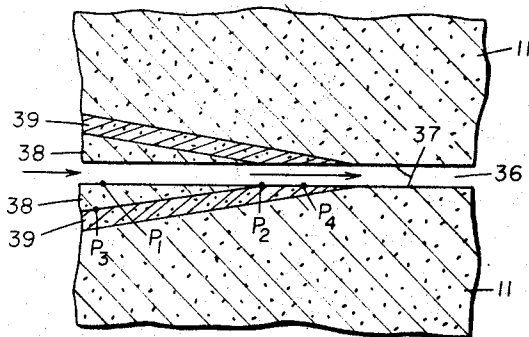


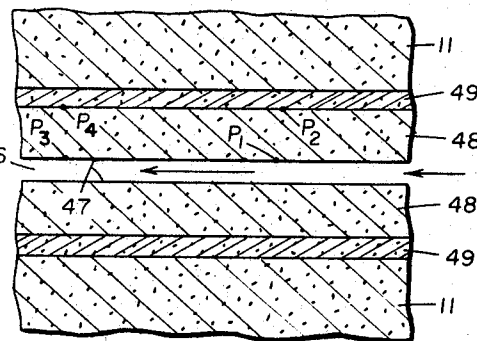
FIG. 1

FIG. 2



STEADY STATE FLOW

FIG. 3



TRANSIENT STATE FLOW

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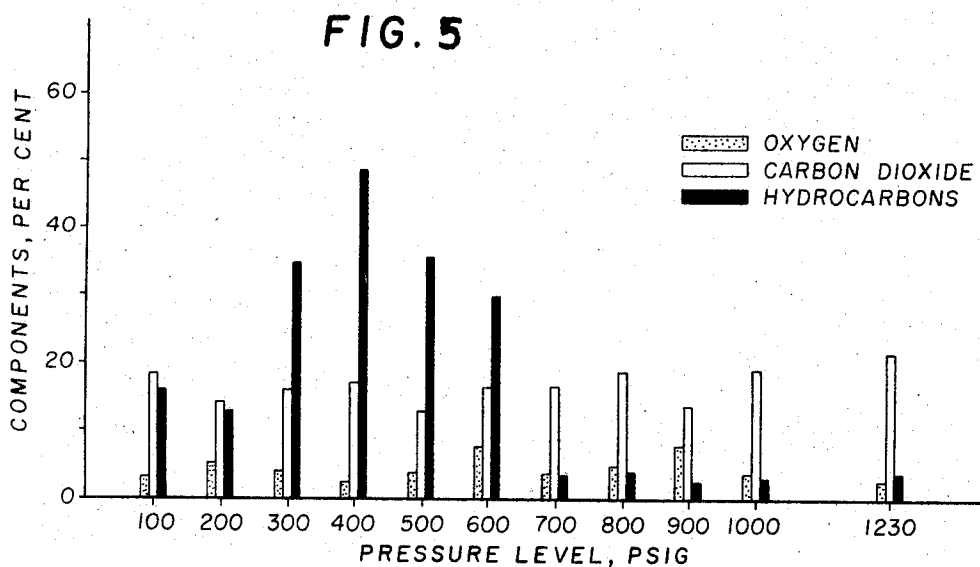
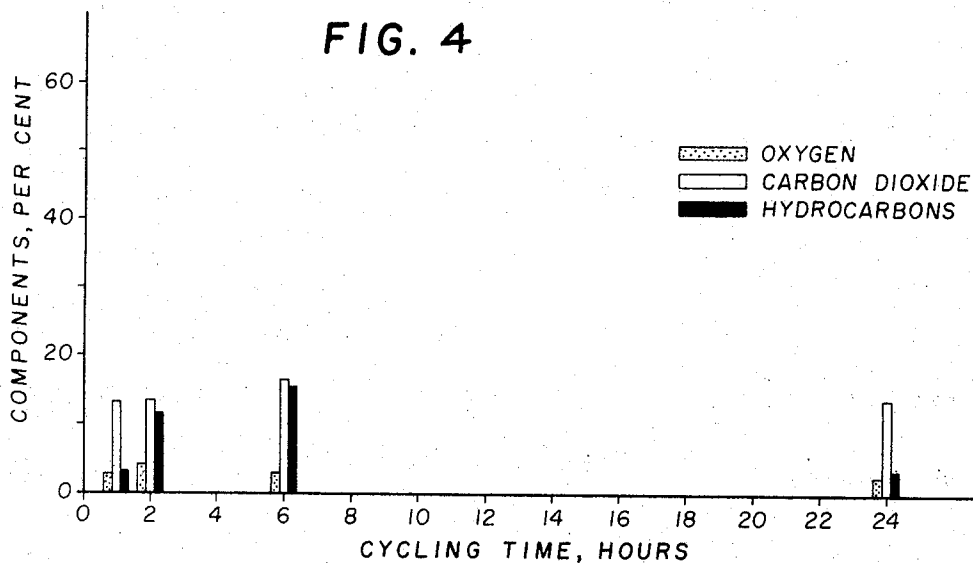
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**IN SITU RETORTING OF OIL SHALE BY
TRANSIENT STATE FLUID FLOWS**

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11 Claims. (Cl. 166-2)

ABSTRACT OF THE DISCLOSURE

This specification discloses: A method for recovering hydrocarbons wherein transient state fluid flows are used to improve the in situ retorting of the oil shale in subterranean formations. More particularly, heating gas is injected into the oil shale to effect combustion of carbonaceous materials therein to generate retorting temperatures. The pressure of the heating gas is continuously increased to maintain transient fluid flowing conditions in the oil shale. Then, the pressurized fluids are removed from the oil shale under continuously decreasing pressures to maintain transient fluid flowing conditions therein. Hydrocarbons are recovered from these fluids. The conditions controlling the injection and removal of the above fluids may be varied, and the resulting changes monitored, to obtain increased recoveries of hydrocarbons.

This invention relates to a method for recovering hydrocarbons from oil shale by in situ retorting. More particularly, it relates to the use of transient state fluid flows for improving the in situ retorting of oil shale in subterranean formations.

Vast oil shale formations residing in many parts of the world are a tremendous source of hydrocarbons. The oil shale formations are comprised of a solid rock, which has an extremely low natural permeability to gases in the range of about 10^{-3} millidarcies or less, interspersed with natural fractures. The fractures permit fluid flows through the oil shale to provide it with a much higher apparent permeability to fluids. Thus, the oil shale without these fractures would be impermeable to fluid flows.

Producing hydrocarbons from oil shale in place requires the application of a conversion process, which includes both heat transfer into and mass transfer out of the oil shale, to effect in situ retorting. The oil shale needs to be heated to above about 500° F. in order to convert the high molecular weight and solid organic material, kerogen, into fluid hydrocarbons. Fluid flows, to remove this finely dispersed fluid from the rock matrix, then are required for its final recovery. Heat transfer into oil shale is severely restricted by its low thermal conductivity and the initial extremely low natural permeability to fluids of the solid oil shale. Further, heat and mass transfer into the oil shale are restricted by the counterflow of the retorted fluids by diffusion induced by concentration and vapor pressure gradients. The movement of fluid is especially restrained by the very low porosity, free void space, of the oil shale; and outside of fractures, generally, the porosity is less than 1 percent.

After the oil shale is retorted free of fluidizable hydrocarbons, there remains a coke residue. The permeability to fluids of the solid retorted oil shale with this coke residue is about 1 millidarcy. Burning this coke residue from this oil shale will increase the permeability to fluids to between 1 and 10 millidarcies. If burning is practiced in the solid oil shale to an extent where inorganic carbonates are decomposed, the permeability to fluids can exceed 100 millidarcies. Thus, it will be seen that fluid movements through the oil shale, outside of fractures, will be heavily restricted under normal conditions even

where it has its greatest permeability, as for example, through decomposition of inorganic carbonates. If it is considered that the surfaces in the oil shale presented even to the fractures are relatively small when compared to the amount of organic matter desired to be converted thermally into hydrocarbons, some means must be provided to increase heat and mass transfer conditions in the oil shale.

For this purpose to effect surface-retorting, the solid oil shale is crushed to particles ranging in sizes from fine powder to several inches on a side. Thus, 40 percent, or more void space will exist in a bed of crushed oil shale. Now the small particles are free to expand and permit a ready outflow of the produced hydrocarbons across small zones of spent shale as retorting is carried out on the crushed oil shale. All of these factors make for comparatively favorable conditions for the conversion and production retorting process. However, in a retorting process in massive subterranean oil shale formations faced with the inherent properties of the oil shale without the oil shale being crushed to small sized particles, both heat transfer and mass transfer must occur across an ever-expanding thickness of spent shale. The spent shale has heat transfer properties similar to an insulating fire brick with equally unfavorable flow properties. Since the oil shale has less than 1 percent porosity and practically no free void space, little or no movement is possible without lifting the overburden strata. These factors all make difficult the effective carrying out of in situ retorting procedures for recovering hydrocarbons from a subterranean oil shale formation, and greatly delay the economic benefits of such process.

It is therefore an object of the present invention to provide a method for the in situ retorting of oil shale where the problems relating to the low porosity, low permeability to fluids, small heat transfer, and restricted mass transfer conditions of the oil shale are largely overcome. Another object is to provide an in situ retorting method wherein the oil shale is heated effectively, predominantly through convection, and in less time than by heretofore known procedures. Another object is to provide an in situ retorting method for recovering hydrocarbons from oil shale in which fluid flows are controlled to increase greatly the heat transfer and mass transfer conditions in the oil shale. Another object is to provide for in situ retorting of oil shale by steps which obtained optimum fluid flowing conditions without the difficulties presented in heretofore known shale oil recovery methods.

These and other objects will become more apparent when read in conjunction with the following detailed description, the appended claims, and the attached drawings, wherein:

FIGURE 1 shows a subterranean formation of oil shale, in vertical section, provided with suitable apparatus for carrying out various embodiments of the method of the present invention;

FIGURES 2 and 3 show the oil shale, of FIGURE 1, in fragmented vertical sections to illustrate a comparison between the in situ retorting of oil shale with fluids flowing in steady state flow and in transient state flow, respectively; and

FIGURES 4 and 5 are charts illustrating the effect of cycling rates, and pressure levels, on transient state fluid flowing conditions in the retorting of oil shale by this invention.

The objects of the present invention are achieved by utilizing transient state fluid flowing conditions by a plurality of novel steps in the in situ retorting of oil shale. These steps provide for retorting the oil shale and for recovering the produced hydrocarbons with more effective utilization of heat energy and greater amounts of recovered hydrocarbons, all in less time, than heretofore

believed obtainable. Certain variations may be practiced for improved recovery of hydrocarbons, and for the optimization of the various steps, so that a maximum recovery of hydrocarbons may be obtained.

Referring to FIGURE 1 of the drawings, there is shown an oil shale 11 provided with suitable apparatus for carrying out the steps of the present invention. The oil shale may be in any formation, as for example, in the Green River Formation of Colorado. This oil shale 11 contains vast quantities of hydrocarbons in the form of kerogen and contains as high as 35 weight percent of kerogen content. The oil shale 11 is usually interspersed with a plurality of fractures, although in some cases it may be void of natural fractures. The oil shale 11 has a low natural permeability to fluids of about 10^{-3} millidarcies or less, with a porosity of less than 1 percent outside of any fractures. For practicing the present method, the oil shale 11 is preferred to be without interconnecting fractures through which fluids are unrecoverably lost. However, the fractures may be sealed with mud, grout, cement, and the like, so that fluids flow only within a restricted area to be retorted.

The oil shale 11 is provided a well means 12 which serves as fluid communication between the earth's surface and the interior portions of the oil shale 11. The well means 12 may comprise a wellbore 13 extended into the oil shale 11 by any suitable means. The wellbore 13 will be usually formed by rotary drilling. Disposed within the wellbore 13 is a casing 14 which extends downwardly from the earth's surface to near the bottom of the wellbore 13. The casing 14 is secured, by suitable means, in fluid-tight relationship with the oil shale 11 and usually with the overburden 15. Preferably, the casing 14 is cemented to the overburden 16 and the oil shale 11 which it contacts. Carried at the top of the casing 14 is a wellhead 17 through which various conductors extend. A conduit 18, for removing pressurized fluids from the oil shale 11, passes through the wellhead 17 and extends downwardly into the lower extremities of the wellbore 13. The conduit 18 carries a valve 19 for regulating the flow of fluids therethrough and connects to a hydrocarbon recovery system where fluids are processed to recover hydrocarbons. The hydrocarbon recovery system is not of a critical nature to this method and, thus, may be of conventional design. Many systems are known, and for this reason, a system is not shown in FIGURE 1. Preferably, the valve 19 is a motor valve controlled by signals supplied from a remote point.

Also, the wellhead 17 carries a conduit 21 connecting a source of heating gas with the oil shale 11. The conduit 21 extends downwardly into the wellbore 13 with its lower terminus provided with a plurality of openings 22 through which heating gas may be dispersed within the wellbore 13. A source of pressurized heating gas is provided and may be of any form, such as a compressor 23, or the like. The compressor 23, at its exhaust, connects to a conduit 24 carrying a control valve 26 and by interconnection with a conduit 27 carrying a valve 28 to the conduit 21. Conduit 27 is connected with a pressure indicator 29 which may be a pressure gauge or a differential manometer. The compressor 23 is driven by a suitable prime mover for compressing the heating gas to elevated pressures. The heating gas then passes through the interconnecting conduits 24 and 27 to the conduit 21 for injection through the openings 22 and the wellbore 13 into the oil shale 11. The pressure at which the heating gas is passed by the wellbore 13 into the oil shale 11 is monitored by the pressure indicator 29. By suitable mechanisms, the pressure at which the heating gas flows can be adjusted automatically through operable interconnection between the pressure indicator 29 and valve 26. A similar system may be used for automatic control of fluid flow in the conduit 18 by interconnection with valve 19. Chain-lines indicate such interconnections. However, manual control of these valves 19 and 26 may be practiced. The

valve 28 may be used in conjunction with the valve 26 to regulate the flow of the heating gas, if desired.

The oil shale 11 about the wellbore 13 may be heated by auxiliary heat sources to temperatures sufficient to effect ignition. For this purpose, an electrical heater 31 can extend to the bottom of the wellbore 13. The upper extremity of the heater 31 passes through the wellhead 17 with suitable electrical interconnection to a source of electrical power. Electrical power may be provided by an alternator 33 driven by prime mover 34 of suitable design. The oil shale 11 surrounding the wellbore 13 may be heated to ignition temperatures by means other than the heater 31, if desired.

The described apparatus are operated in general for injecting a heating gas into the wellbore 13 in conjunction with heating of the adjacent oil shale 11 to ignition temperatures whereby in situ combustion is effected of carbonaceous materials therein. The valve 19 is closed at this time. The oil shale 11 is continued to be heated to temperatures of about 500° F. or higher, and after the oil shale 11 surrounding the wellbore 13 is in part retorted, the injection of heating gas is terminated through the closing of valve 26. Now the valve 19 is opened to convey the pressurized fluids from the oil shale 11 through the wellbore 13 outwardly to the hydrocarbon recovery system connected thereto. With the valve 28 open, the pressure at which the heating gas is injected, and the fluids are removed, from the oil shale 11 via the wellbore 13 is monitored by the pressure indicator 29. Thus, the well may be cycled between the injection of heating gas, to effect heating by in situ combustion for retorting the oil shale, and for depressuring the wellbore 13 to effect removal of the pressurized fluids from the oil shale 11 with recovery of the hydrocarbons that they contain. The oil shale 11 and the related apparatus which have been described for effecting this procedure are considered to be conventional and various other arrangements may be utilized, including more than one wellbore spaced in fluid interconnection within the oil shale 11.

The term "heating gas" as used herein is intended to include a gas selected from the group consisting of oxygen-containing gases singularly or in various proportions and combinations with combustible and noncombustible gases. The heating gas may be preheated initially at the surface by suitable equipment to a temperature sufficient to ignite spontaneously a portion of the carbonaceous materials in the oil shale 11. The combustion of such materials produces heat to decompose the kerogen into hydrocarbons and to move the resultant hydrocarbons in the oil shale 11. The heating begins with the oil shale surfaces adjacent the wellbore 13 and produces a combustion front which migrates outwardly through the oil shale 11. The combustion front moves progressively, radially outwardly from the well means depending upon the heat transfer conditions in the oil shale 11.

The temperature and the velocity of the resulting combustion front can be regulated by adjusting the temperature, volume, and pressure of the heating gas being introduced, or its oxygen content. However, since air is the most inexpensive source of heating gas, the only considerations are temperature, pressure, and volume of the heating gas. The oil shale 11 is preferably heated to a temperature above 500° F., and preferably between 500° F. and 1100° F. Temperatures below 500° F. are ineffective commercially to decompose the kerogen portion of the oil shale 11 into shale oil products.

Combustible gases may also be injected into the oil shale 11 and therein ignited when the hydrocarbon content of the oil shale is relatively low, when initiation of combustion is difficult, or for other reasons. Such combustible gases can provide the only fuel used for heating the shale or to supplement the carbonaceous materials or kerogens present as natural fuel in such oil shale 11. The combustible gases may be injected into the oil shale 11 through the well means 12 separately or in combination

with oxygen-containing gases. It may be found desirable in certain aspects of operation to inject alternately the oxygen-containing gases and the combustible gases into the oil shale 11. Noncombustible gases may be admixed with the injected gases to assist in controlling the temperature of the combustion front, if desired. The particular composition of the heating gas is not critical in this invention.

Prior to describing the present method, an orienting description of the flow states possible during the in situ retorting of oil shale is believed helpful. The flow of fluids in priorly known in situ retorting methods has been in the steady state. In the steady state, a pressure differential exists between spaced locations in the oil shale 11 which does not change significantly in magnitude with time, although the pressures creating this differential at these locations may be slowly changing. Referring now to FIGURE 2, a portion of the oil shale 11 receives a flow of the injected heating gas through a fracture 36 to effect in situ retorting with fluid flows in the steady state. The fracture 36 is assumed to be in fluid communication with the wellbore 13 and an external vent with the heating gas flowing at a constant pressure from left to right as illustrated by the arrows. Combustion is effected along the surfaces 37 of the oil shale 11 along the fracture 36. The zones 38, of the oil shale 11, are burned clean of carbonaceous material. In zones 39 remains a carbonaceous residue after heating has decomposed kerogen into fluid hydrocarbons. The heating gas enters the fracture 36 at a constant pressure P_1 . The pressure P_2 downstream in the fracture 36 is reduced by the naturally occurring pressure drop. At a location in the oil shale 11 normal to the fracture 36, there will be at equilibrium established a pressure P_3 in the clean zones 38. The pressure difference between pressures P_1 and P_3 is slight, being created by the concentration gradient of materials flowing countercurrently to the heating gas between these two pressure-locations and the thermally increased vapor pressure of the retorted products at P_3 so that the pressures P_1 and P_3 are substantially the same for practical purposes. In the coked zones 39, the fluid hydrocarbons, from conversion of the kerogen, cannot move at the pressure P_3 toward the near equal pressure P_1 . Also, these fluids would have to move countercurrently to the flow of heating gas. For this reason, these fluid hydrocarbons in coked zone 39 at the location of the pressure P_3 must move angularly downstream toward a point of reduced pressure P_4 . Since the difference between pressures P_1 and P_2 is determined by pressure drop in the open fracture 36, and the fluids flowing in the zone 39 are subject to much greater restriction, then pressure P_4 must be located downstream of pressure P_2 to establish fluid flows thereto from the location of P_3 into the fracture 36. A substantial flow path must then exist, in steady state flow, to move hydrocarbons from the location of pressure P_3 , into the fracture 36. The products of the retorting and combustion reactions are moved from the interior of the oil shale 11 into the fracture 36 to mix with the flow of the heating gas. These fluids are removed from the fracture 36 and processed to recover the hydrocarbons.

As a result of steady fluid flow, the heating gas only has a very low diffusion, or "forced," flow perpendicularly into the oil shale 11 induced by concentration-pressure gradients so that great amounts of time are required to produce a given quantity of hydrocarbons, and also with a low oxygen utilization. The hydrocarbons, from the conversion of kerogen, must move through the oil shale 11 nearly parallel to the combustion front existing in the zones 39 whereby large quantities of these hydrocarbons are consumed in this front and in the excess free oxygen traversing the fracture 36. Thus, it is seen that the steady state flow of fluids employed for retorting the oil shale 11 must result in a relatively low production of hydrocarbons even from those small amounts converted from the kerogen. Also, this reduced recovery

of hydrocarbons from the oil shale 11 takes great lengths of time because of restricted fluids flow. A large amount of carbon residue in the coked zones 39 remains out of contact with the oxygen needed to consume it. The basic problems appear to reside in heat transfer obtained primarily by conduction and with mass transfer through only diffusion (molecular) flow in long flow paths in the steady state flow of fluids employed for in situ retorting.

The present method of in situ retorting of oil shale 11 is carried out employing fluids in a transient state of flow. A great multiplication in heat and mass transfer quantum is obtained principally by "forced" fluid flows. There is also a corresponding greatly increased production and recovery of hydrocarbons in less time than such quantity of hydrocarbons can be obtained with steady state fluid flows. The term "transient state" flow of fluids is herein employed to define the flow of fluids in response to an increasing pressure differential existing between spaced points in the oil shale, and the pressures at those points creating the differential pressure are constantly changing unidirectionally in magnitudes with time. With reference to FIGURE 3, the oil shale 11 has a fracture 46 with one end sealed and the other in fluid communication to the well bore 13. The fracture 46 receives, at a constant unidirectionally changing pressure, heating gas in a flow from right to left in the direction of the arrows. The oil shale 11 adjacent the fracture 46 is heated sufficiently to effect ignition whereby an in situ combustion front results along surfaces 47. The zones 48 of the oil shale 11 are burned clean of organic material by the advance of such front. Zones 49 are heated by the front sufficiently to convert the kerogen into fluid hydrocarbons with only a carbonaceous coke remaining as residue. This coke is later consumed by the in situ combustion front moving normally and outwardly into the oil shale 11 to provide heat for retorting the virgin oil shale 11.

The heating gas passed into the fracture 46 at ever-changing pressures maintains a transient state condition of fluid flow in the oil shale 11. Thus, the pressures of the heating gas at any location in the oil shale 11 will be ever changing in magnitude with time. More particularly, pressures P_1 and P_2 , at spaced locations on a line normal to the fracture 46, are always of different magnitudes and changing at different rates. The pressure P_1 always changes at a greater rate than pressure P_2 so that a pressure differential increasing in magnitude with time is established throughout the transient state flow of fluids in the fracture 46. A natural pressure drop downstream from the location of pressure P_1 will produce pressure P_3 in the fracture 46. There will be a differential in pressure between pressure P_3 and pressure P_4 at a location on a line normal to the fracture 46 in the oil shale 11. The differential between the pressures P_1 and P_2 will be substantially the same in magnitude as between pressures P_3 and P_4 although there is also a differential in pressure between P_1 and P_3 .

When the pressure of the heating gas within the fracture 46 is increasing, the pressure differentials also increase between P_1 , P_2 and P_3 , P_4 to maintain continuously the flow of fluids outwardly in the oil shale 11 for effecting in situ retorting. When the pressurized fluids in the fracture 46 are removed at ever-decreasing pressure, the pressure differentials also increase but the directional flow of fluids is reversed. However, the continuous fluid flows from the oil shale 11 into the fracture 46 are again obtained. Thus, in either event, the increasing pressure differentials between the pressures P_1 , P_2 and P_3 , P_4 and also between P_1 and P_3 continuously induced flow of fluids between the locations of the pressures P_1 and P_2 and likewise between P_3 and P_4 into the fracture 46 and then out of the oil shale 11. Fluids do not flow appreciably from the location of pressure P_2 through the oil shale 11 to pressure P_3 in the fracture 46 since the differential between pressures P_1 , P_2 is obviously greater than between pressures P_1 , P_3 . As a result, heat and mass transfers are

accelerated by a continuous movement of fluids substantially perpendicularly between the oil shale 11 and the fracture 46. Thus, in situ retorting is principally obtained by convection in the fluids moved perpendicularly between the fracture 46 and the interior of the oil shale 11. This results in a greatly increased heating of the oil shale 11 by the continuous penetration of the heating gas over the shortest flow path from the fracture 46, and of like advantage, in the rapid and thorough removal of the hydrocarbons produced by conversion of the kerogen into the fracture 46 and the well bore 13 to facilitate recovery of the hydrocarbons. In summary, transient state fluid flows maintain pressure gradients increasing continuously within the oil shale 11 to stimulate greatly by convection the heat transfer and mass transfer required to retort effectively the oil shale 11 in situ.

A laboratory experiment and mathematical model study were carried out to determine the effective differences between transient state and steady state flow regimes illustrated in FIGURES 3 and 2, respectively. From this work, it can be shown in applying fluid flows in the transient state, a 2½ foot thick zone of depleted oil shale (like coked zone 49) from a fracture can be flushed at a closed boundary between normalized pressure levels of .98 and .65 in .55 hour for the depressuring to atmospheric from a given maximum pressure. For the same mass flow at the given maximum pressure, but under steady state flow conditions, the time required is roughly 13.8 hours. Also, data from the in situ retorting of samples of oil shale has shown, under similar comparable pressure and mass flow rates, that the steady state flow illustrated in FIGURE 2 produces a flow path between pressure locations P_3 and P_4 , twelve times as long as the flow path between the locations of P_1 and P_2 under the transient state fluid flow illustrated in FIGURE 3. Thus, a very obvious great improvement is obtained in heat transfer, and mass transfer, conditions by the employment for in situ retorting of the transient state flow in accordance with this invention rather than the steady state flow of fluids of prior known procedures.

With the foregoing understanding of the basic premises of steady state flow versus transient state flow, a preferred embodiment of the invention will be described now with reference to FIGURE 1. As a first step of this method, heating gas is injected for a first period of time through the well means 12 into the oil shale 11 from the conduit 21. The heating gas, supplied by the compressor 23, is regulated by the valve 26 for injection into the oil shale 11. Conjunctively, the oil shale 11 adjacent the wellbore 13 is heated to ignition temperatures to effect in situ combustion of the resident carbonaceous materials. For this purpose, the heating gas may be preheated at the earth's surface of the heater 31 may be operated on energy supplied by the current source 33 driven by the prime mover 34. After in situ combustion is obtained, the injection of the heating gas is continued at ever-increasing pressures to maintain transient state fluid flowing conditions in the oil shale 11. For this purpose, the valve 26 may be adjusted manually. Preferably, the valve 26 is automatically controlled from pressure indicator 29 which monitors the pressure at which heating gas is injected into the oil shale 11. Means other than valve 26 may be used to arrange the injection of the heating gas into the oil shale 11 at ever-increasing pressures, if desired. The rate of increasing the pressures of injection of the heating gas between upper and lower pressure limits may be contingent upon a time basis which insures the continuous diffusion of the various fluids by transient state flow into the oil shale 11. However, the injection pressures should be ever increasing so that transient state fluid flowing conditions are maintained in the oil shale 11. The injection of the heating gas under these conditions is continued until elevated pressures are obtained. The injection of the heating gas into the oil shale 11 ends at a maximum pressure below the magnitude which induces fracturing in the

oil shale 11. At this time, the valve 26 in the conduit 27 is closed. Obviously, it is undesirable to continue injecting the heating gas while propagating fractures into the oil shale 11 since the products of the in situ retorting would be lost to extremities of the oil shale 11 from where they cannot be recovered.

Another step of the method is practiced after the injection of the heating gas is ended. The pressurized fluids contained in the oil shale 11 resultant from the preceding steps are removed under transient state flow through the conduit 18 from the well means 12 with regulation of fluid flow by the valve 19. The pressurized fluids from the conduit 18 are applied to a hydrocarbon recovery system in which the hydrocarbons retorted from the oil shale 11 are recovered. The valve 19 is employed to regulate the flow through the conduit 18 of fluids removed from within the oil shale 11 at ever-decreasing pressures to maintain transient fluid flowing conditions in the oil shale 11. The valve 19 can be adjusted manually. Preferably, the valve 19 is controlled automatically by arrangement with the pressure indicator 29, which with valve 28 open, reflects the pressure of fluids entering the wellbore 13 from the oil shale 11. The rate of decreasing pressures may be of the same magnitude as described for the injection of the heating gas into the oil shale 11. However, it is desired that the pressure decrease at a sufficient rate that the liquid hydrocarbons in the pressurized fluids in contact with the heated oil shale 11 do not undergo unacceptable thermal degradation into gases.

Usually, the duration of the first and second periods of time (in which the injection of heating gas and the removal of the resultant pressurized fluids from the oil shale 11 are obtained) is extended periodically as the retorting progresses through the oil shale 11. This is of advantage since the flow path normal to the fracture 46 in the oil shale 11 between the location of pressures P_1 and P_2 increases as the in situ retorting proceeds. Consequently, both heat transfer and mass transfer by fluid flow, and conduction, are maintained relatively constant in rate across an ever-expanding thickness of the clean zones 48. The spent oil shale in zones 48 has a heat transfer property similar to an insulating fire brick with fluid-flow properties equally unfavorable. A greater oxygen utilization and greater recovery of the resultant hydrocarbons in the pressurized fluids are obtained by periodically extending the duration of said first and second periods.

It is also preferred as retorting continues, for the same reasons as described for extending the duration of the first and second periods, that the maximum pressure level of the injected heating gas in the first-mentioned step is periodically increased as retorting progresses through the oil shale. By increasing the pressure, a greater mass transfer by fluid flows is obtained through the areas of the clean zones 48. Thus, the differential between P_1 and P_2 may be increased to foster greater mass transfer and heat transfer conditions.

It has been found that an improvement in the porosity of the oil shale subject to in situ combustion can be correlated with the steps of the present method so that even greater mass transfer and heat transfer relationship can be established in the employment of the transient state fluid flows as heretofore described. More particularly, with reference to FIGURE 3, the oil shale 11 between fractures, prior to retorting, usually has less than 1 percent porosity although the coked zones 49 have an improved porosity from the degradation of the kerogen into hydrocarbons. Further, the mean pore size in the coked zones 49 for a 25-35 gallon per ton oil shale is found by measurement to have a dimension of about 0.1 micron, which varies slightly but proportionally with its kerogen content. In the clean zones 48 freed of coke, particularly when subjected to temperatures suitable to decompose the carbonate constituents, the average pore sizes are much greater than the 0.1 micron dimension in the coked zones 49. Thus, one major limiting factor in the retort-

ing of the oil shale 11 is the small average pore size in the coked zones 49.

Laboratory results have shown, with reference to FIGURE 3, that the total flow of the gases under transient state flow conditions through the clean zone 48 and the coke zone 49 into contact with the oil shale 11 is in the Knudsen regime where the mean free path of the heating gas is larger than the average pore diameter of the coke zone 49. However, the practical operational pressure levels, through which increasing pressures and decreasing pressures of the step of the present invention are unidirectionally changed, may be sufficiently increased until the mean free path of the heating gas becomes smaller than the average diameter of the pores in the coke zones 49 and then the fluid flows are in the Poiseuille regime.

In both the Knudsen and the Poiseuille regimes, the total fluid flow will include diffusional flow resulting from concentration gradients and the forced flow resulting from the pressure gradients developed by the two mechanisms: (a) pyrolysis reactions resulting in large volume increases as the kerogen is converted to liquid and gaseous products; and (b) the pressure drop imposed on the fluids flowing through the fracture 46 under pressure differentials. Thus, in both flow regimes, the total volumetric transport depends on the pressure or concentration gradient existing across the pore.

In the Knudsen regime where diffusional, or molecular, flow predominates over "forced" flow, the mass rate of flow is proportional to the concentration or partial pressure gradient between spaced locations for each fluidized component; and the constant of proportionality is termed the diffusion coefficient. This coefficient varies inversely with the absolute pressure in the system and therefore attains its highest value at low pressures, i.e., sub-atmospheric. While this coefficient is high at low pressures, the expelling force from concentration (or partial pressure) gradients between spaced locations is small so that the total mass transport is low.

However, at elevated pressures where flow is in the Poiseuille regime, the "forced" flow predominates over diffusional flow and the mass flow rate is proportional to the pressure gradient with the constant of proportionality decreasing as the absolute pressure increases. This constant is similar to the permeability coefficient in Darcy's equation.

The significance of the statements regarding the Knudsen and Poiseuille regimes becomes more apparent when considered with the following equations which define these regimes.

In the Knudsen regime, the rate of heating gas flow through a single pore may be given by the following Equation 1:

$$\frac{dn}{dt} = \frac{8}{3} \frac{\pi r^3}{\sqrt{2\pi M R T}} \frac{\Delta p}{\Delta x} \quad (1)$$

where:

dn/dt is the flow in number of molecules per second

r is the radius of the pore

M is the molecular weight

R is the gas constant

T is the absolute temperature

$\Delta p/\Delta x$ is the partial pressure gradient along the pore (or $\Delta c/\Delta x$ where using the concentration gradient).

Capillary diffusional flow results in pressure ranges at which the mean free path of the fluid is greater than the mean pore diameter in the coked zones 49. Thus, in this pressure range changing the partial pressure, or concentration, gradient across a pore results only in a proportional increase of the mass flow transfer through the pore.

In the Poiseuille regime with predominant "forced" flow, the rate of heating gas flow through a single pore may be given by Equation 2:

$$\frac{dn}{dt} = \frac{8}{3} \frac{\pi r^4}{\lambda \sqrt{2\pi M R T}} \frac{\Delta p}{\Delta x} \quad (2)$$

where λ is the mean free path of the gas and the other constants are as defined for Equation 1. In the above regime, the total mass transport through a pore is dependent upon the pressure or concentration gradient existing across the pore in this pressure range but the mass transport through the pore is markedly increased by increases in pressure gradient across the pore.

The mean free path λ of a gas molecule is related generally to pressure p , by the Equation 3:

$$\lambda = \frac{10^{-5}}{p \text{ (atm.)}} \text{ cm.} \quad (3)$$

In practice, the flow in both regimes described by Equations 1 and 2 can be combined into Equation 4:

$$\frac{dn}{dt} = \frac{8}{3} \frac{\pi r^3}{\sqrt{2\pi M R T}} \frac{\Delta p}{\Delta x} \left(1 + \frac{3\pi r}{64 \lambda} \right) \quad (4)$$

The terms are as defined for the previous equations.

At all pressures at which the mean free path of the gas is larger than the mean diameter of the pores in the coked zone 49, the flow of fluids is within the Poiseuille regime and the rate of heating gas flow, or other pressurized gas flow, is described by Equation 1.

For all pressures at which the mean free path of the gas is smaller than the mean diameter of the pores in the coke zone 49, the flow of fluids is within the Poiseuille regime and the rate of heating gas flow, or other pressurized gas flow, is described by Equation 2.

It has been found, as previously explained, that the mean average diameter of pores in the coke zones 49 of the oil shale 11 is about 0.1 micron. Increasing the pressure level from 1 to 10 atmospheres across a pore of this size causes the heating gas flow rate (corrected to standard conditions) to increase through the pore approximately 18-fold. This result can be calculated from the foregoing equations and has been substantiated by laboratory experiments and model studies. The same emphasized result of mass flow is found relative to the clean zones 48. If Darcy's law is used for comparative proof, assuming the permeability constant to be the same at both pressures, the volumetric rate of flow would increase about 33-fold. In one laboratory experiment, the volumetric rate of air flow (corrected to standard conditions) is shown to increase 26-fold by increasing the pressure level from 1 to 10 atmospheres across the pores in coked zones 49. The calculated permeability constant decreased from about 3.3 millidarcies to an asymptotic value of 1.5 millidarcies over the same range of pressures. Thus, operating transient flows of fluids in the oil shale 11 at pressures where the mean free path of the gas phase is less than the mean pore diameter of the coked zone 49 provides about a 20-fold increase there-through in the volumetric flow rate of fluids. This flow-rate improvement increases all of the desirable factors relating to the retorting and recovering of hydrocarbons from oil shale 11. Particularly, oxygen utilization is greatly increased, and due to the mass and heat transfer increases which result, greater portions of the oil shale 11 can be retorted in less time, and much greater amounts of hydrocarbon can be recovered, than could be obtained by transient flow conditions at pressures where the fluid flow is defined by the Knudsen regime, i.e., where the mean free path of the gas phase is larger than the mean average pore diameter of the coke zones 49.

The steps of the present method in a preferred aspect include the injection of the heating gas, under transient fluid flowing conditions, at elevated pressures where the injected gas molecules have a free path less than the average pore radius of the porous matrix of the oil shale 11 subjected to in situ combustion, particularly in the coke zones 49. Thus, there will be a great increase in the volumetric rate of heating gas flow with all the aforementioned advantages in the retorting of the oil shale 11. It has been found that these advantages can be obtained in shale in the Green River Formation by increasing the

pressure levels in the injection of heating gas at transient flow conditions to above 10 atmospheres. Inasmuch as the oil shale 11 to be retorted usually resides at relatively great depths below the surface of the earth, pressures extending significantly above this 10-atmosphere level can be used without inducing fracturing in the oil shale 11.

The same advantageous results may be obtained in the step where pressurized fluids are removed from the oil shale 11 through the well means 12. Generally, the pressure levels in this step will be arranged to conform with those of the preceding step so that the injection of heating gas terminates at the level where removing of pressurized fluids begins, and begins at the pressure where removal of pressurized fluids from the oil shale 11 ends so that a true cyclic procedure may be practiced with great facility.

It is of special utility in the steps of injecting the heating gas and removing the pressurized fluids from the oil shale 11 that the injection of heating gas begin at a first pressure of sufficient magnitude where the injected gas molecules have a free path about equal to the average pore radius of the porous matrix of the oil shale 11 subjected to in situ combustion, particularly the coke zones 49; and that the injection end at an elevated pressure greater in magnitude than the first pressure, but not of sufficient magnitude to induce fracturing in the oil shale 11. Thus, the entire injection of the heating gas under conditions effecting a transient state in the flow of fluids in the oil shale 11 takes place in a range of pressures in the Poiseuille regime so that the greatly multiple increase in the volume-rate of heating gas flow through the pores of the oil shale 11 is obtained. Likewise, the removing of the pressurized fluid from the oil shale 11 begins at about the second pressure where the injection of the heating gas was terminated, and ends when the pressurized fluids in the oil shale 11 are about the first pressure where the injection of heating gas began. Thus, a cyclic program for effecting greatly increased recovery of hydrocarbons from oil shale with a corresponding decrease in the time required to obtain such recovered hydrocarbons will be effected.

It has been found in the present method that by certain improved steps even greater improvements in the recovery of hydrocarbons from the oil shale 11 can be ob-

streams, particularly the volume and composition of the pressurized fluids removed from the oil shale, adjustments can be made to the basic steps of the present invention for increasing the recovery of hydrocarbons from the pressurized fluids. Further, by making certain adjustments to the conditions under which these steps are practiced, a maximum recovery of hydrocarbons can be obtained.

It has been found that the duration of the first and second periods, where injection of heating gas and the removal of pressurized fluids are obtained, the maximum pressure level to which the heating gas is injected, and the difference between this maximum pressure and the least pressure to which the pressurized fluids are removed, is adjusted, either singularly or conjunctively, so as to increase the recovery of hydrocarbons from the pressurized fluids. Further, making particular adjustment to each of these conditions for practicing the basic steps of this invention provides a maximized recovery of hydrocarbons from the pressurized fluids.

In example, the step of monitoring the volume and composition of the pressurized fluids removed from the oil shale 11 through the wellbore 13 is practiced. The apparatus, and oil shale structure in which it is employed, may be substantially as shown in FIGURE 1 for this purpose. The step of monitoring the volume and composition of the pressurized fluids provides information from which adjustment may be made to the steps of this procedure for increasing the recovery of hydrocarbons from the pressurized fluids.

The steps of the present invention were practiced in a field test, along with monitoring of the volume and composition of the pressurized fluids removed from the oil shale 11, in the Green River Formation in Colorado. Particularly, the steps of the present invention were practiced with the maximum pressure levels of the injected heating gas successively increased in 100 p.s.i.g. increments from 100 p.s.i.g. to 500 p.s.i.g. in cycles from atmospheric pressure. The duration of the first and second periods was held substantially constant with a variation only between a 4- and 6-hour duration. The bottom-hole temperatures were also monitored. The composition and volume of the pressurized fluids removed in the conduit 18 were monitored. The information obtained is reported in the following Table I:

TABLE I

Pressure Level, ¹ p.s.i.g.	Rate of Cycling Time, hrs.	Average BHT, ° F. ²	Pressurized Fluids Analyses				
			Percent O ₂	Percent CO ₂	Percent CO	Percent H ₂	Percent Hydrocarbon
100.....	6	1,030	2.1	16.9	3.4	2.2	15.7
200.....	6	1,010	4.8	13.3	2.1	1.4	12.6
300.....	4	1,220	3.5	15.5	4.5	3.7	33.0
400.....	5	1,060	1.3	16.3	8.6	12.6	49.6
500.....	5	1,010	2.8	11.9	4.6	2.8	34.6

¹ Maximum injection pressure above atmospheric pressure.

² Average bottom-hole temperature.

tained. To facilitate practicing such improved steps, in reference to FIGURE 1, means are provided to monitor the volume and the composition of pressurized fluids removed from the oil shale 11 through the conduit 18. Any means may be used to measure the volume of pressurized fluid in the conduit 18. Gas analysis, performed by any suitable means on the pressurized fluids, may show the hydrocarbon, oxygen, carbon dioxide, carbon monoxide, and hydrogen contents of the pressurized fluids. If desired, bottom-hole temperatures within the wellbore 13 may also be taken. The amount of oxygen and related gases contained in the heating gas injected through the conduit 21 into the oil shale 11 may be monitored so that oxygen utilization and hydrocarbon production can be obtained by comparison of the analysis made on the flow of fluids in the conduits 21 and 18. It has been found that from the information obtained by analysis of these fluid

In Table I, it will be observed that by cycling of the injected heating gas/air from atmospheric pressure to a pressure level maximum of 400 pounds and removal of the pressurized fluids down to atmospheric pressure, a 5-hour duration for the first and second periods of time produced a maximum hydrocarbon recovery and with a maximum consumption of oxygen in the heating gas. The maximum pressure levels, above and below this 400-pound pressure, produce lesser amounts of hydrocarbons in the same amount of time. From this information in Table I, it is of great facility to adjust the basic steps of this invention for a pressure cycle between atmospheric and 400 p.s.i.g. from the information obtained by monitoring the volume and composition of the pressure fluids so as to increase the recovery of hydrocarbons from the pressurized fluids. For example, if the steps of the present invention were operated at 300 p.s.i.g. maximum pres-

sure level for the injecting heating gas, then the pressure level may be readily increased to 400 p.s.i.g. for the same duration of the first and second periods of time to obtain about a 30 percent increase in hydrocarbon recovery from the pressurized fluids removed from the oil shale 11 through the conduit 18.

Likewise, other information obtained from monitoring the volume and composition of the pressurized fluids can be used to advantage. There is shown graphically in FIGURE 4 additional information derived by cycling the well means 12 between atmospheric and 100 p.s.i.g. maximum pressure levels for the injected heating gas and removed pressurized fluids for durations of the first and second periods of $\frac{3}{4}$, 2, 6, and 24 hours. The information, displayed in bar-graph style, indicates that about the 6-hour duration for the first and second periods produces a maximum hydrocarbon production and also a maximum oxygen utilization, a minimum oxygen content, and a maximum carbon dioxide content, in the pressurized fluids removed from the oil shale 11. Thus, the information obtained from this step may be used for varying the conditions in the rate of pressure cycling in the steps of this procedure to improve greatly the recovery of hydrocarbons.

Again, by monitoring the volume and composition of the pressurized fluids removed from the oil shale 11, and from the information obtained, it is possible to adjust the pressure differential which produces transient fluid flowing conditions, during the steps of injecting the heating gas and removing the pressurized fluid, to improve hydrocarbon recovery. In FIGURE 5, a graphic display of the information thus obtained shows the effect of magnitude changes in differential pressure between minimum and maximum pressures on composition of the produced pressurized fluids. For this purpose, the well means 12 were employed in the steps of the method with the heating gas injected from atmospheric to several different maximum pressure levels. These pressure differentials ranged from 100 p.s.i.g. to 1230 p.s.i.g. as displayed in FIGURE 5. The oxygen, carbon dioxide and hydrocarbons contents are illustrated in bar-graph styles. From FIGURE 5, clearly a pressure change from atmospheric to 400 p.s.i.g. levels for the injected heating gas and removed pressurized fluids provided maximum hydrocarbon recovery. Similarly, the oxygen utilization for the injected heating gas (air) was the greatest as shown by a minimum residual oxygen content and a maximum carbon dioxide production. The magnitude of the pressure differential producing these results is dependent upon the range of pressures through which the change of pressure is effected. However, the range of pressures over which transient-state fluid flows are made can be adjusted to obtain an increased recovery of hydrocarbons by these steps for any magnitude of pressures.

The step of monitoring the volume and composition of the pressurized fluids removed from the oil shale provides information on which the conditions of practicing the basic steps of this invention are varied, one at any time, until an increased recovery of hydrocarbons may be obtained. Then, after adjustment to these steps as required to increase the hydrocarbon recovery and information determined by the preceding steps, the steps again can be repeated until a substantial quantity of hydrocarbons is recovered from the shale. More particularly, through the information obtained in the described manner, the duration of the first and second periods of time, during which the injection of heating gas and removal of pressurized fluids occur, respectively, is adjusted to produce an increased recovery of hydrocarbons from the pressurized fluids. Similarly, the maximum pressure level to which the heating gas is injected and pressurized fluids removed is adjusted to produce an increased recovery of hydrocarbons from the pressurized fluids. Likewise, the pressure differential between maximum injection pressure and minimum removal pressure which pro-

duce transient fluid flowing conditions in the oil shale 11 is adjusted to produce an increased recovery of hydrocarbons from the pressurized fluids.

Varying each of the conditions under which the basic steps are practiced and then repeating the step adjusted from information obtained will produce a maximum recovery of hydrocarbons. More particularly, each of the conditions under which the basic steps are practiced is varied with monitoring of the volume and composition of the pressurized fluids removed from the oil shale 11. During this time, the duration of the first and second periods of time during which the heating gas is injected and the removal of pressurized fluids occurs, respectively, is adjusted to produce an improved hydrocarbon recovery; the maximum pressure level to which the heating gas is injected into the oil shale 11 is adjusted to produce an increased recovery of hydrocarbons; the pressure differential producing transient fluid flowing conditions in the oil shale 11 during the injection of heating gas into and the removal of pressurized fluids from the oil shale 11 is adjusted to produce an increased recovery of hydrocarbons; and these steps practiced conjunctively provide a maximum of recovery of hydrocarbons in retorting in situ the oil shale 11. The variation and adjustments of these steps can be practiced in any order to the same effect without loss of advantage.

It has been found that, at some time during the practice of these steps, it may be desired to increase further the permeability of the clean zones 48 in the oil shale 11. For this purpose, the maximum pressure level to which the heating gas is injected, and the duration of the first and second periods of injecting the heating gas and removing the pressurized fluids, are adjusted so the bottom-hole temperature within the wellbore 13 increases sufficiently to decompose the carbonate constituents in the oil shale 11. This results in producing large concentrations of carbon dioxide beyond that which is indicative normally of the consumption of the oxygen in the heating gas. Thus, the permeability of the clean zones 48 may be greatly increased to foster greater increases in mass and heat transfers therethrough from the fluids flowing between the fracture 46 and the interior of the oil shale 11. Also, practicing these steps at certain elevated temperature conditions influences the range of hydrocarbon products produced by pyrolysis of the kerogen. Thus, the conditions for these steps may be varied and adjusted so as to provide a maximum, or an increased, recovery of a desired, or optimum, range of hydrocarbon products.

No exact mathematical criterion or relationship between the various conditions under which the steps of this invention are practiced can be established at this time. For this reason, it is necessary to rely upon intentional variation in the conditions under which these steps are practiced to obtain the information which allows adjusting the step conditions for the increased recoveries of hydrocarbons from the pressurized fluids and, where desired, to increase to a maximum the recovery of hydrocarbons thus produced.

It will be apparent from the foregoing that there has been herein described a method employing the transient flows of fluids in the injection of heating gas and the removal of pressurized fluids from oil shale to produce a greatly increased recovery of hydrocarbons by in situ retorting than heretofore could be obtained and in a much reduced period of time. Various changes and alterations to the steps of this invention may be made without departing from its scope, and it is intended that such changes and variations be encompassed within the scope of the appended claims. For this reason, it is intended that the present description of this invention is to be taken as illustrative and not limitative for the purposes of definition in the present claims.

What is claimed is:

1. A method for the in situ retorting of oil shale mass

having well means in fluid communication therewith, comprising the steps:

- (a) injecting for a first period of time a heating gas from the well means into the mass of oil shale with heating of said oil shale to a temperature sufficient to effect combustion of the carbonaceous materials contained therein, said injection carried out at ever increasing pressures to maintain transient fluid flowing conditions in the oil shale, ending said injection of heating gas at a maximum pressure less than sufficient in magnitude to induce fracturing in the oil shale, and thereafter,
- (b) removing by the well means for a second period of time the resultant pressurized fluids from the oil shale, which received the heating gas, at ever decreasing pressures to maintain transient fluid flowing conditions in the oil shale, and recovering hydrocarbons from the pressurized fluids removed from the oil shale.

2. The method of claim 1 wherein the duration of the first and second periods is extended periodically as retorting progresses through the oil shale.

3. The method of claim 1 wherein the maximum pressure level of the injected heating gas is periodically increased as retorting progresses through the oil shale.

4. A method for the in situ retorting of oil shale mass having well means in fluid communication therewith, comprising the steps:

- (a) injecting for a first period of time a heating gas from the well means into the mass of oil shale with heating of said oil shale to a temperature sufficient to effect combustion of the carbonaceous materials contained therein, said injection being carried out at ever increasing pressures to obtain transient fluid flowing conditions in the oil shale with a substantial portion of said injection of heating gas being made at pressures where the injected gas molecules have a free path less than the average pore radius of the porous matrix of the oil shale after subjected to in situ combustion, ending said injection of heating gas at a pressure of less than sufficient in magnitude to induce fracturing in the oil shale, and then,
- (b) removing by the well means for a second period of time pressurized fluids from the oil shale which received the heating gas at ever decreasing pressure to maintain transient fluid flowing conditions in the oil shale, and recovering hydrocarbons from the pressurized fluids removed from the oil shale.

5. A method for the in situ retorting of oil shale mass having well means in fluid communication therewith, comprising the steps:

- (a) injecting for a first period of time a heating gas from the well means into the mass of oil shale under in situ combustion conditions at pressures increasing continuously to maintain transient state fluid flowing conditions for establishing a pressure gradient in the oil shale matrix adequate to effect heating of same to at least retorting temperatures, said injection beginning at a first pressure of a sufficient magnitude where the injected gas molecules have a free path about equal to the average pore radius of the porous matrix of the oil shale after subjected to in situ combustion and said injection ending at a second pressure greater in magnitude than the first pressure and yet not of sufficient magnitude to induce fracturing in the oil shale, and then,
- (b) removing by the well means for a second period of time pressurized fluids from the oil shale which received the heating gas at continuously decreasing pressures to maintain transient state fluid flowing conditions beginning at about the second pressure and ending when the pressurized fluids in the oil shale are at about the first pressure, and recovering hydrocar-

bons from the pressurized fluids removed from the oil shale.

6. A method for the in situ retorting of oil shale mass having well means in fluid communication therewith, comprising the steps:

- (a) injecting for a first period of time a heating gas from the well means into the mass of oil shale with heating of said oil shale to a temperature sufficient to effect combustion of the carbonaceous materials contained therein, said injection carried out at ever increasing pressures to obtain transient fluid flowing conditions in the oil shale, ending said injection of heating gas at a pressure of less than sufficient in magnitude to induce fracturing in the oil shale,
- (b) removing by the well means for a second period of time pressurized fluids from the oil shale which received the heating gas at ever decreasing pressure to maintain transient fluid flowing conditions in the oil shale, and recovering hydrocarbons from the pressurized fluids removed from the oil shale,
- (c) monitoring the volume and composition of the pressurized fluids removed from the oil shale and on the basis of the information thus obtained,
- (d) making adjustment to the steps (a) and (b) as required for increasing the recovery of hydrocarbons from the pressurized fluids, and then,
- (e) repeating the adjusted steps (a) and (b) until hydrocarbons are removed in a substantial quantity from the oil shale.

7. A method for the in situ retorting of oil shale mass having well means in fluid communication therewith, comprising the steps:

- (a) injecting for a first period of time a heating gas from the well means into the mass of oil shale with heating of said oil shale to a temperature sufficient to effect combustion of the carbonaceous materials contained therein, said injection carried out at ever increasing pressures to obtain transient fluid flowing conditions in the oil shale, ending said injection of heating gas at a pressure of less than sufficient in magnitude to induce fracturing in the oil shale,
- (b) removing by the well means for a second period of time pressurized fluids from the oil shale which received the heating gas at ever decreasing pressure to maintain transient fluid flowing conditions in the oil shale, and recovering hydrocarbons from the pressurized fluids removed from the oil shale,
- (c) monitoring the volume and composition of the pressurized fluids removed from the oil shale while varying one of the conditions at any time under which the steps (a) and (b) are practiced until an increased recovery of hydrocarbons is obtained,
- (d) repeating the steps (a) and (b) with the adjustment to these steps required to increase the recovery of hydrocarbons as determined in step (c), and then,
- (e) repeating the adjusted steps (a) and (b) until a substantial quantity of hydrocarbons is recovered from the oil shale.

8. The method of claim 7 where in step (c) the duration of the first and second periods of time, during which the injection of heating gas and removal of the pressurized fluids occur, respectively, is adjusted to produce an increased recovery of hydrocarbons from the pressurized fluids.

9. The method of claim 7 where in step (c) the maximum pressure level to which the heating gas is injected into the oil shale is adjusted to produce an increased recovery of hydrocarbons from the pressurized fluids.

10. The method of claim 7 where in step (c) the pressure differential producing transient fluid flowing conditions in the oil shale during the injection of heating gas into, and the removal of pressurized fluids from, the oil shale is adjusted to produce an increased recovery of hydrocarbons from the pressurized fluids.

11. A method for the in situ retorting of oil shale mass

having well means in fluid communication therewith, comprising the steps:

- (a) injecting for a first period of time a heating gas from the well means into the mass of oil shale with heating of said oil shale to a temperature sufficient to effect combustion of the carbonaceous materials contained therein, said injection carried out at ever increasing pressures to maintain transient fluid flowing conditions in the oil shale, ending said injection of heating gas at a pressure of less than sufficient in magnitude to induce fracturing in the oil shale, 5
10
- (b) removing by the well means for a second period of time pressurized fluids from the oil shale which received the heating gas at ever decreasing pressure to maintain transient fluid flowing conditions in the oil shale, and recovering hydrocarbons from the pressurized fluids removed from the oil shale, 15
- (c) monitoring the volume and composition of the pressurized fluids removed from the oil shale while varying each of the following conditions under which the steps (a) and (b) are practiced until a maximum recovery of hydrocarbons is obtained: 20

- (1) the duration of the first and second periods of time during which the injection of heating gas and removal of the pressurized fluids occur, respectively;
- (2) the maximum pressure level to which the heating gas is injected into the oil shale; and
- (3) the pressure differential producing transient fluid flowing conditions in the oil shale during the injection of heating gas into, and the removal of pressurized fluids from, the oil shale.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,362,471

January 9, 1968

Marion L. Slusser et al.

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 5, line 13, for "pressuree" read -- pressure --; column 6, line 62, for "pressure" read -- pressures --; column 7, line 53, for "of" read -- or --; column 12, line 21, for "presurized" read -- pressurized --; same column 12, TABLE I, in the heading to the third column, line 3 thereof, for "° F.₁" read -- ° F.₂ --; column 13, line 63, for "quantity" read -- quantity --; column 14, line 55, for "obtained" read -- obtain --; column 16, line 28, for "removed" read -- recovered --.

Signed and sealed this 25th day of February 1969.

(SEAL)

Attest:

Edward M. Fletcher, Jr.

Attesting Officer

EDWARD J. BRENNER

Commissioner of Patents