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OIL RECOVERY FROM OIL SHALES BY TRANSVERSE COMBUSTION

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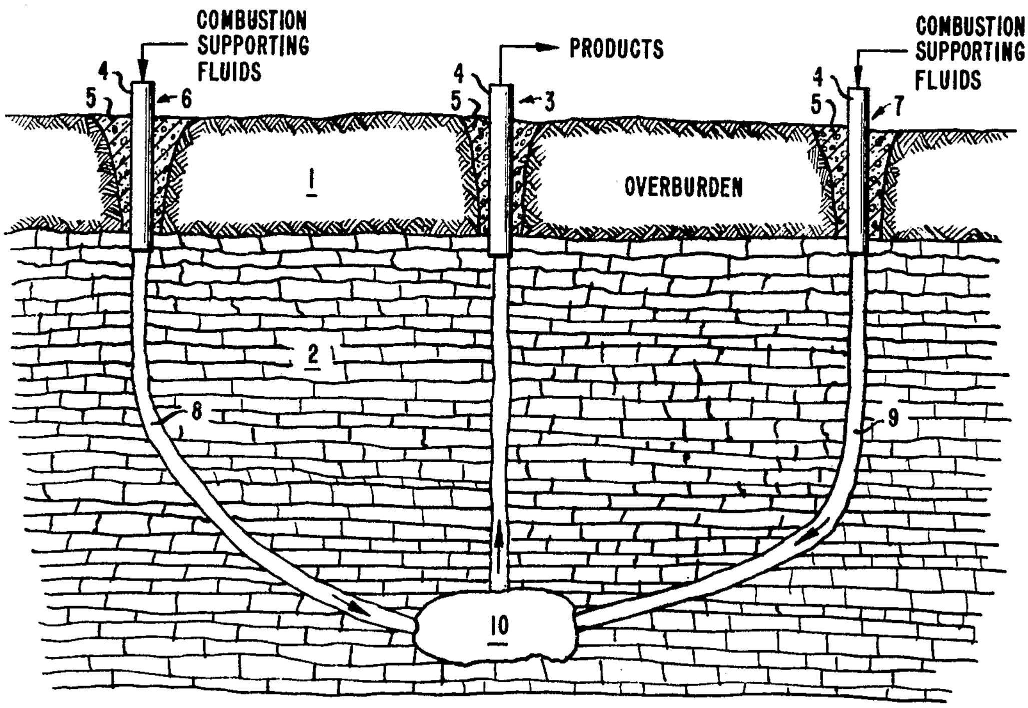

FIG. 1

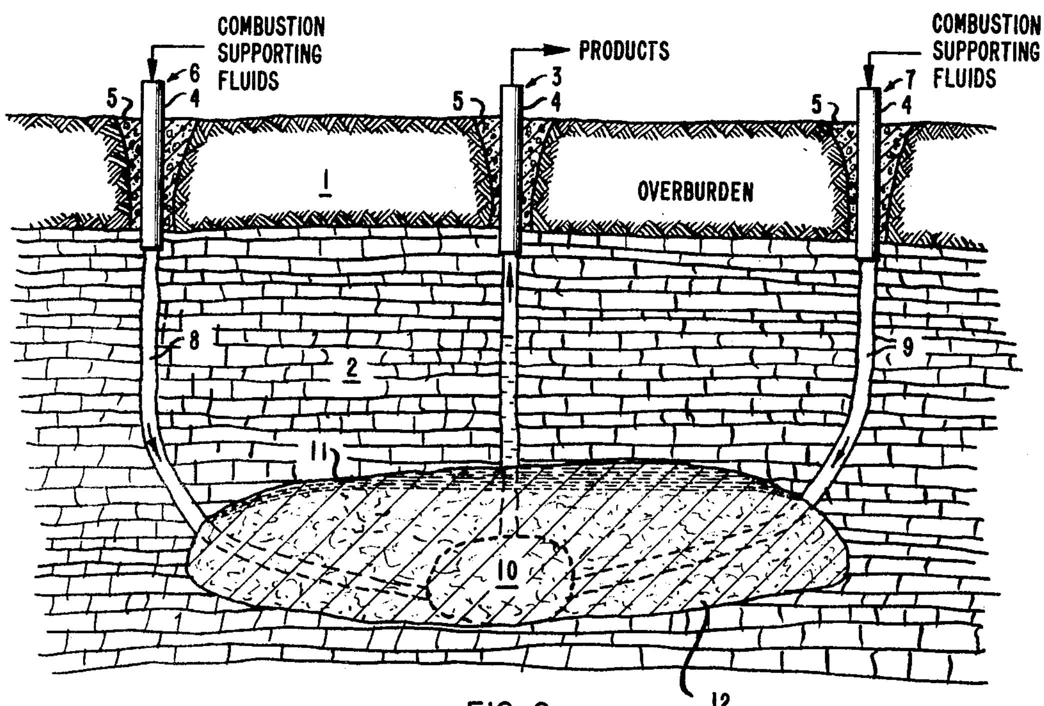

FIG. 2

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HIS AGENT

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OIL RECOVERY FROM OIL SHALES BY TRANSVERSE COMBUSTION

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ABSTRACT OF THE DISCLOSURE

A process of recovering hydrocarbon products from subterranean oil shale formations by drilling at least two spaced boreholes into the formation in a manner such that the lower terminal ends of the boreholes approach convergence adjacent to the bottom of the formation. Sufficient oil shale is removed in the area of convergence to form a shale expansion chamber communicating at all times with the lower terminal ends of the boreholes and in situ combustion is established in the chamber. A combustion-supporting fluid is supplied through at least one of the boreholes to maintain the combustion within the chamber and cause a combustion front generally parallel to the bedding planes of the formation to move vertically and upwardly through the formation generally perpendicular to the bedding planes of the formation and between the converging boreholes. Finally, vaporous effluent produced in the combustion is recovered from the formation through at least one of the boreholes.

This invention relates to the recovery of hydrocarbon products from oil shales and, more particularly, to a method of recovering hydrocarbons from underground shale deposits by a novel in situ retorting technique.

Looking to the future, oil shales are essentially thought of as an important energy source as the reserves of petroleum crudes dwindle. Even today in those countries which are deficient in conventional crudes, such as Great Britain and Sweden, hydrocarbons from oil shales are being presently produced. Since it has proved feasible to extract hydrocarbons or hydrocarbon products from oil shales on an industrial scale, producers look critically at oil shales for replacement of the dwindling supply of crude petroleum. Further, the availability of enormous deposits of oil shales in various parts of the world, which is estimated at 1.2 to 2 trillion barrels, warrants considerable expense and development of better techniques to recover hydrocarbon products from these vast oil shale deposits.

Organic matter in these vast oil shale deposits is often referred to as kerogen and is unlike either petroleum or coal types of organic matter. Further, oil shales are an intermediate hydrocarbon-bearing substance having properties considerably different than either petroleum or coal, since the oil shales contain appreciable amounts of inorganic matter, generally well above 33%, as distinguished from coal which contains very minute amounts and petroleum which is substantially free of inorganic matter. Oil shales should not be classified with rocks which actually contain impregnated petroleum, such as the Athabasca sands (tar sands) of Alberta, Canada, and represent a separate, distinct source of hydrocarbons having sharply contrasting physical characteristics.

In recovering the organic matter or hydrocarbons from oil shales, one must remain cognizant of the physical characteristics of the shale. Oil shale, is usually a dense, tough, resistent and impermeable substance. In general, the oil shales are regularly bedded and, with few exceptions, thinly laminated. Rhythmatic laminations are by far the most frequent type and are due to regular alternation of

micro-granular layers of carbonate and clay with layers of structureless organic matter. In some high grade varieties of oil shales, the lamination is not apparent until after the rock has been heated and the hydrocarbon products driven off. However, close examination will generally reveal the laminar characteristics of the shales and the bedding planes are generally flat except where deformation has occurred caused by tectonic movement.

Many investigators have concluded that commercial production of hydrocarbons from oil shales should be handled in a retorting type process using mined shale which is crushed or broken up before the retorting is carried out. Since as much as 90% of the material handled will be waste mineral matter, the logistical problems in handling the mined shale become enormous. Further, waste disposal problems of the spent shale become difficult and finely divided spent shale is difficult to handle. In addition, the natural leaching of the spent shale in a large dumping area can cause serious ground water pollution problems which requires that the handling of spent shale be carefully controlled. In view of these problems, in situ retorting of the oil shale has considerable inherent value since the expense of materials handling is alleviated and the disposal problems of spent shale is avoided. Likewise, mechanical equipment used to dig, mine, haul and crush the shale are not required and these factors reduce the costs of in situ combustion processes provided such processes yield feasible recovery.

In situ retorting deserves special consideration in view of many advantages mentioned above. To date, the retorting of oil shale in situ is generally divided into two classes. In one type, relatively large drift-size mine workings were dug into a flatlying oil shale after which the walls of the drift were blasted to fill the drift with broken shale. Then, by closing off the openings at one end with suction devices and applying combustion-supporting fluids at the opposite ends, it is possible to burn the broken shale filling the drifts and recover hydrocarbons therefrom. In this technique, quantitative recovery is low and performance was generally poor in many respects. Probably one of the main difficulties of such a process is the necessity to remove prior to treatment a quantity of shale equal to about a third of the amount of shale treated to make room for the broken rock filling the drifts during treatment of the shale.

A second type in situ combustion is described in U.S. Pat. 3,149,670 issued to Grant which is carried out by drilling two closely spaced boreholes, establishing communication therebetween, and carrying out an in situ combustion process where the heat front moves from one well to the other. See also U.S. 2,780,449 issued to Fisher et al.

Processes such as those mentioned in the patents have been only moderately successful caused by the lack of primary permeability of the oil shales. They require combustion fronts moving through the formation from injection to production wells utilizing artificially induced fractures and in this manner fail to utilize fully the secondary permeability created in the burned region as a result of the laminar character of oil shales. The present invention is a vast improvement over those known prior art processes in that it employs a generally horizontal combustion front at all times extending from injection to production well(s) which moves vertically from bottom to top of the formation through the oil shale. This type of a combustion front, extending generally parallel to the bedding planes and moving through the oil shale in an upward direction more or less perpendicular to the bedding planes, has substantial advantages since the combustion front is more easily maintained and the flow of combustion-supporting fluids can travel along and between the laminates of the oil shale as permeability is created by splitting or spalling of the shale due to the burning and heating effect of the combustion reaction.

More specifically, the instant invention involves an in situ combustion process in underground oil shale formations which includes the steps of (1) drilling at least two spaced boreholes into the shale formation in a manner that their lower terminal ends will approach convergence at the bottom of the reservoir, (2) removing oil shale in the area of convergence to form a chamber having communication with the lower terminal ends of the boreholes, (3) establishing in situ combustion within the chamber, (4) supplying combustion-supporting fluids via one of the boreholes, and (5) recovering hot vaporous effluents from the formation produced by the in situ combustion via one of the boreholes. Utilizing this method, a generally horizontal combustion front is established in the bottom of the shale formation which burns upwardly through the formation with increasing radius and at all times extending from injection to production well(s).

By the use of this novel method of in situ combustion, several of the major difficulties experienced in the in situ combustion process for recovery of hydrocarbons from oil shales can be avoided. Probably, the major problem overcome is that of maintaining fluid communication between the spaced boreholes used in such processes, which, in conventional processes, requires high gas pressures to force hot gases through the artificially created fractures connecting the boreholes. Further, as the hot gases pass through such fractures, they tend to close because of the expansion of the unspent shale heated by exhaust gases and the entry into the fracture of viscous petroleum products. Closer spacing of the boreholes helps these problems, but is not practical from the economic point of view. It should be appreciated that in the instant invention, there is no problem in the closing of fractures or the necessity of high gas pressures to force gases through the shale since both the injection boreholes supplying the combustion-supporting fluids and the production boreholes for recovering the hydrocarbon products all communicate with a common cavern in the base of the oil shale reservoir. Further, the curvature of the boreholes provides satisfactory borehole spacing controlling the lateral dimensions of the front and making the process practical from an economic standpoint.

Since the combustion-supporting fluid is supplied to the combustion front burning from the bottom of the reservoir toward the top from one or more wells located generally around the periphery of the cavern, the combustin-supporting fluid to the combustion front is supplied transverse to the vertical movement of the front. Thus, this process of in situ combustion recovery of oil shales can be termed a transverse in situ combustion process, since the combustion-supporting fluid is supplied across the combustion front rather than perpendicular to it as in prior art processes.

The general description above will be more easily understood by reference to the specific description covering the drawings wherein:

FIG. 1 shows a cross-section of an earth formation having a subterranean oil shale stratum penetrated by several boreholes, and

FIG. 2 is the same cross-sectional view of the same formation showing conditions in the reservoir subsequent to the initiation of the recovery process according to this invention, and at an intermediate stage.

Referring to FIG. 1 and 2, which show the same reservoir wherein the process of this invention is being employed, FIG. 1 shows the preparation of the reservoir for initially carrying out the process and FIG. 2 shows an intermediate stage of the process as it is being carried out in the reservoir. While in actual practice, a plurality of converging boreholes would be employed to achieve better results, the process can be amply illustrated by the three borehole pattern shown in the FIGS. 1 and 2. Also, it should be appreciated that the process could be carried out by the use of only two converging boreholes. However, three or more are usually preferred.

As illustrated in FIG. 1, three boreholes are drilled through the overburden 1 into an underground shale reservoir 2; the central borehole **3** is drilled vertically down into the reservoir 2 and is cased through the overburden with casing **4** which is sealed in the overburden with a sealant **5**, such as cement. Borehole **3** extends vertically downward into the shale reservoir **2** terminating near the bottom reservoir and is uncased below the overburden **1**. The two outer boreholes **7** and **6**, respectively, laterally spaced from the central borehole **3**, are also cased only through the overburden with casings **4** which like the casing **4** of borehole **3** are secured in the overburden with a sealant **5**.

The lower portions **8** and **9** of boreholes **6** and **7** are not cased and are directionally drilled so as to approach convergence or actually converge at the base of the shale reservoir **2** and in the vicinity of borehole **3**. Actually, the art of directional drilling is well known and competent drillers can hit a target area about 10 feet square in the base of reservoir **2** without undue difficulty. Tools for directionally drilling boreholes are covered by numerous U.S. patents, for example see U.S. 2,669,430 issued to Zubin and U.S. 2,906,499 issued to Travis. Occasionally, the converging boreholes **8** and **9** may actually intersect with one another or borehole **3** when drilled. However, this is not necessary for the practice of this invention. Generally, it is only necessary to hit a target area in the base of shale reservoir **2** so that the respective ends of boreholes **3**, **5** and **6** will be within such a distance of one another that explosives or fracturing fluids can be introduced through the respective boreholes to effect a fluid communication between them. The distance will be preferably within 10 or 20 feet of one another however larger distances may be satisfactory which depends on the physical characteristics of a particular oil shale.

Conventional fracturing techniques with fluids, explosive or nuclear devices can be used to establish fluid communication between the lower terminal ends of the boreholes **3**, **5** and **6** in the target area located at the base of oil shale reservoir **2**, and in most cases, such fracturing will usually be necessary where the several boreholes do not actually intersect during the drilling operation because of the fluid impermeability of oil shale formations.

After fracturing has been completed, a cavern **10** is formed within the target area to connect the various boreholes with one another and to provide space for the initial expansion of the unspent oil shale as it is heated by the combustion reaction. Normally, chamber **10** can be formed by conventional techniques, such as the use of acids which will dissolve the carbonates, drilling, bailing or other removal techniques to remove a quantity of the shale within the target area at the base of reservoir **2** or drilling devices for enlarging the terminal ends of the boreholes adequately to provide sufficient shale removal to practice the invention.

A preferred sequence of operations may be to drill the central borehole **3** first, set off a large explosion in the bottom of the hole and follow this by drilling the directional boreholes **6** and **7**. When the latter holes reach the area where the rock has been shattered by the explosion, the fractured oil shales will be drilled up and circulated to the surface and the required cavern **10** will be formed. If necessary, additional explosions or leaching with acids followed by cleaning out with a drill bit can be employed. It will be desirable, however, that the cavern be at least partly filled with crushed oil-shale as this will facilitate ignition. In addition to crushed shale, a propping agent such as sand or gravel can be placed in the cavern to prevent closing of same by the expanding shale when heated.

The maximum space initially required can be calculated from the expansion coefficient and the heat conductivity of the oil-shale and the temperature and areal extent of the combustion front during ignition.

In some cases, the use of chamber **10** may not be required where the several boreholes are terminated within a very small target area so that subsequent expansion of the unspent oil shale will not close off the communication between their respective terminal ends. However, in most cases, because of the excessive expansion of oil-shales when they are heated, it will be necessary to form chamber **10** at the base of formation **2** in order to start and maintain the combustion front satisfactorily.

After cavern or chamber **10** has been formed at the base of the reservoir **2** in the target area and provides substantial communications between the several boreholes penetrating the shale formation **2**, the second phase of the invention may be carried out which can be better understood by reference to FIG. 2. Initially, it is necessary to establish combustion within chamber **10** at the base of the shale reservoir **2** which can be accomplished in numerous ways. For example, a burner assembly may be introduced into chamber **10** and supplied with fuel and combustion-supporting fluids from any one of the several boreholes. If a heater is used, it would probably be lowered in borehole **3** since this would be the most convenient, but the combustion can be established in many other ways. For example, pyrotechnical devices can be introduced into the chamber **10** and both combustion-supporting fluids and combustible fluids supplied to the chamber through the boreholes **3**, **6** or **7**. Once the combustion reaction has been established in chamber **10**, the natural tendencies of heated materials to rise will cause the greater temperature to occur along the top of chamber **10** and for the most part, a generally horizontal combustion front will be formed across the top of chamber **10** though some burning will occur at other locations.

After the combustion front is established, the unspent oil shale around chamber **10** will begin to expand but since chamber **10** is void of or only partly filled with crushed and broken oil shale, this expansion will not be sufficient to close chamber **10** or impede fluid communication between the terminal ends of all the boreholes communicating therewith. Thus, the expansion of the oil shale will not "kill" the combustion front and some initial space is provided. Naturally, chamber **10** must be of sufficient size so as to avoid shutting off or "killing" the combustion front.

Once the shale has been ignited the process becomes self sustained as kerogen is removed from the shale and the spent-shale or ash becomes permeable to the combustion supporting fluids.

In the embodiment of the invention shown in the FIGS. 1 and 2, the central borehole **3** is used as the recovery borehole and the directionally-drilled, converging boreholes **6** and **7**, are used to supply combustion-supporting fluids for the combustion front established at the top of chamber **10**. Also, if desirable, or necessary because of the low quality of the shale, the combustion-supporting fluids may also contain combustible materials, such as hydrocarbon gases, in order to ensure that combustion continues to occur in chamber **10** as it grows larger. However, in most cases, the oil shale itself will provide sufficient fuel for the combustion front and it will be unnecessary for the addition of combustible-supporting materials with the combustion-supporting fluids injected into the chamber via the several boreholes **6** and **7**, respectively. It may be also advantageous to inject water with the combustion supporting fluids. Water will be converted to steam, resulting in a more uniform heat distribution across the combustion front and lower the reaction temperature thus increasing yield. It also will recover heat from the burned out region, filling this area with water and in this manner preventing accummulation of hydrocarbon products below the front, thus improving the effectiveness of the process.

Referring now to FIG. 2, wherein the process of this invention has been employed for a period of time, the changes occurring in the reservoir can be seen. Quite generally, the combustion front **11** originally established at

the top of chamber **10** has expanded horizontally to encompass a much larger portion of the reservoir, burning further radially outwardly from borehole **3** along the curving, upwardly-diverging, lower portions **8** and **9** of boreholes **6** and **7**. Further, this burning of the oil shale has greatly enlarged chamber **10** so that it encompasses a much larger portion of the reservoir as can be seen by reference to the dotted lines in FIG. 2 which represents the original conditions in the reservoir prior to the expansion of a combustion front **11**. The growth of the combustion front adds greatly to the economy of this process since fewer wells are required to treat the same volume of the reservoir **2**. As shown in FIG. 2, chamber **10** has become greatly enlarged and is filled with spent shale ash **12** left from the vertical, upward-burning of the combustion front. This provides a natural gravity separation of the spent shale from the unburned shale in the vicinity of the combustion front which facilitates the vertical movement of the front. However, since the chamber **10** provided for the initial expansion of the shale caused by the heating, the enlarged chamber **10** in FIG. 2 does not require additional space to avoid highly compressive loads across the combustion front **11**. Further, the spent shale ash **12** from which the kerogen has been removed is gas permeable along the bedding planes and through cracks in a direction perpendicular to the bedding and the combustion-supporting fluids can flow from the lower portions **8** and **9** of boreholes **6** and **7** respectively, through the ash **12** towards and along the combustion front **11**.

In addition, another substantial advantage is gained by this process which is the ability of the combustion-supporting fluids to travel generally along the laminar bedding planes of the unspent shale formation to combustion front **11**. This is important since as the shale is heated, it tends to spall off from the ceiling of chamber **10** as a laminant which allows the combustion-supporting fluids to be present on both sides of the laminar bedding planes of the shale as it is being consumed by the combustion front **11** which materially facilitates combustion.

As combustion front **11** moves vertically upwardly through the shale reservoir **2**, it converts a substantial quantity of the structureless organic material or kerogen to vaporous hydrocarbon products which, in the embodiment of the invention shown in the drawings, travel vertically up through borehole **3** with the other products of the combustion from the combustion front **11**. These products can subsequently be recovered by suitable condensing and separating equipment.

It should also be appreciated that a plurality of boreholes can be used in carrying out this process and actually it is probably desirable to have at least four directionally-drilled, converging boreholes in the target area which is penetrated by a central borehole for the recovery of the gaseous effluents from the combustion. In some cases, 6, 8 or more converging boreholes will be used depending on conditions.

In comparing FIG. 1 with FIG. 2, it can be seen that one of the novel features of this invention is that the combustion front extends at all times from injection well(s) to production well(s) and continues to increase in size and moves up through the shale formation thereby exposing more and more of the oil shale reservoir to the combustion front which, of course, increases total recovery and the volume treated. The actual growth of the combustion front as it proceeds vertically up through the shale reservoir **2** is limited by the degree of divergence obtainable between the upper portion of boreholes **6** and **7** and this in turn, is limited somewhat by the thickness of the shale formation. Generally, the process works exceptionally well in oil shale reservoirs having thicknesses from 300 to 600 feet or greater.

The minimum thickness of the shale required to carry out the process will be predominantly controlled by economic reasons which depend on the kerogen content of the shale and the depth at which these beds are encountered.

Exploitation of thinner shale reservoirs, e.g., less than 100 feet thick, may impose some limitations on the use of this process due to the limited degree of curvature obtainable by directional drilling. This is not thought to be a serious limitation, however, and possibly could be overcome by less conventional drilling techniques such as right angle drilling.

It has also been proposed to drill a cluster of overlapping patterns which are simultaneously ignited. Each pattern would include at least an effluent production borehole and a closely spaced combustion-supporting fluid injection borehole. The combustion area of each pattern would emanate upward from the terminate ends of the said boreholes in the manner of an inverted cone. Although each pattern would singularly exploit only one third of the proximate layer of oil-shale, a much greater yield may be realized by causing the combustion fronts of several patterns to grow together at some vertical distance above the terminal depth. This distance will depend on the amount of overlap of the individual patterns.

EXAMPLE

As an illustrative example of the process of the present invention, several laboratory experiments have been carried out as described below:

A 44-inch long, 4-inch diameter massive oil-shale core, which has been drilled perpendicular to the bedding planes, is cemented inside a thin walled 4-foot long, 4½-inch diameter steel tube which in turn is mounted inside a high pressure vessel. Two parallel ½-inch diameter holes, with 2⅝-inch distance between centers, are drilled lengthwise through the core serving as injection and production wells. At one end of the core, two ¼-inch stainless-steel tubes are cemented approximately 2 inches inside the ½-inch holes to provide connections for the injection and production lines. This side of the tube is equivalent to the surface under actual field conditions. At the other end, the two ½-inch holes are in communication through a one-inch long cylindrical space filled with crushed oil shale. The crushed material is kept in place by a three-inch long oil-shale core plug. A 1⅜-inch diameter hole is drilled through the center of this plug in which a stainless-steel heater-well is inserted extending through the crushed material approximately one-inch into the oil-shale core. This side of the tube is equivalent under actual field conditions to the bottom of the bore holes which are in communication through a common chamber or cavern **10** as indicated in FIG. 1. For accurate control during the experiments, nine thermocouples are mounted along the axis of the core at equal distances of five inches.

After packing off both ends, an electric heater is inserted into the heater well and the pressure in the pressure vessel is increased to approximately 200 p.s.i. A combustion supporting gas, in this case air or a mixture of 50 percent oxygen and 50 percent nitrogen is circulated through the core by injecting into the ½-inch injection well at pressures ranging from 125 p.s.i. to 175 p.s.i. Initially the gas passes through the crushed oil-shale and is produced back through the ½-inch production well. Prior to ignition, the combustion supporting gas is injected and produced at a low rate equivalent to approximately 0.2 cubic feet per minute. After ignition, the flow rate is increased and may vary from 0.4 to 0.6 cubic feet per minute. Ignition occurs when the temperature reaches 1000 to 1200° F. and a combustion front starts to move through the core at a rate of about 3 inches per hour, countercurrent to the flow of the combustion supporting gas in the injection well. The temperature of the front is approximately 1200° F. and sometimes increases to 1600° F. which can be reduced by the injection of water. Usually an experiment is terminated 10 to 12 hours after ignition. Production of exhaust gas, oil and water is carefully measured. Oil production depends greatly on the kerogen content of the oil shale which has varied from 12 to 40 gallons per ton Fisher assay. The gravity of the produced oil ranges from 18.0° API to 32° API, the lower gravity oil being produced during the initial stages of the experiment. Respective viscosities range from 40 to 7 centipoise. After terminating an experiment, the core is lifted from the pressure vessel, the steel tube is cut and together with the cement carefully removed. Inspection of the core shows that the spent shale behind the front become very friable and flaky, displaying a high degree of permeability along the bedding planes.

It should also be observed that the one-inch space filled with crushed oil-shale is not intrinsic to the experiment. In one particular experiment, a space of only ⅛ inch filled with sand grains was used. The experiment proceeded in the same manner as those described above, the only difference being that ignition time was increased from approximately two hours to nine hours.

As can be appreciated from the above description, this novel approach to the in situ combustion of oil shales solved many of the problems existing in the prior art processes and represents a practical solution to in situ combustion of oil shales.

I claim as my invention:

1. A process of recovering hydrocarbon products from subterranean, oil shale formations which comprises the steps of:

(a) drilling at least two spaced boreholes into a subterranean, oil shale formation in a manner that their lower terminal ends approach convergence substantially parallel to the bedding planes of the formation and adjacent to the bottom of said oil shale formation;

(b) removing sufficient oil shale in the area of convergence to form a shale expansion communicating at all times with said lower terminal ends of said boreholes;

(c) establishing in situ combustion within said chamber;

(d) supplying a combustion-supporting fluid through at least one of said boreholes to maintain said in situ combustion within said chamber and to cause a combustion front generally parallel to the bedding planes of the formation to move vertically and upwardly through said formation generally perpendicular to the bedding planes of said formation, the lateral dimensions of the combustion front being controlled by the converging spaced boreholes and the combustion-supplying fluid being supplied generally along the laminar bedding planes of the unspent shale formation and transverse to the movement of the combustion front; and

(e) recovering vaporous effluent from said formation produced by said in situ combustion through at least one of said boreholes.

2. A process according to claim **1** including the step of treating the vaporous effluents recovered from said formation to recover useful hydrocarbons.

3. A process according to claim **1** including the step of casing the boreholes drilled into the oil shale formation only to a depth above where they traverse said formation.

4. A process according to claim **1** including the step of drilling a central borehole and at least four boreholes laterally spaced from said central borehole so that their lower terminal ends approach convergence with the lower terminal end of said central borehole.

5. A process according to claim **4** including the step of recovering the vaporous effluents from said formation produced by the in situ combustion through said central borehole and supplying combustion-supporting fluid to said in situ combustion through said four boreholes laterally spaced from said central borehole.

6. A process according to claim 1 including the step of combining a combustible material with said combustion-supporting fluid for facilitating the in situ combustion.

7. A process according to claim 1 including the step of combining water with said combustion-supporting fluid for further improvement of the in situ combustion process.

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166—259, 261, 247