United States Patent

[11] 3,537,528

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[54] **METHOD FOR PRODUCING SHALE OIL FROM AN EXFOLIATED OIL SHALE FORMATION**
6 Claims, 6 Drawing Figs.

[52] U.S. Cl. 166/247, 166/259, 166/261, 166/272
[51] Int. Cl. E21b 43/24
[50] Field of Search 166/247, 256, 259, 261, 268, 272, 271, 299, 257, 303

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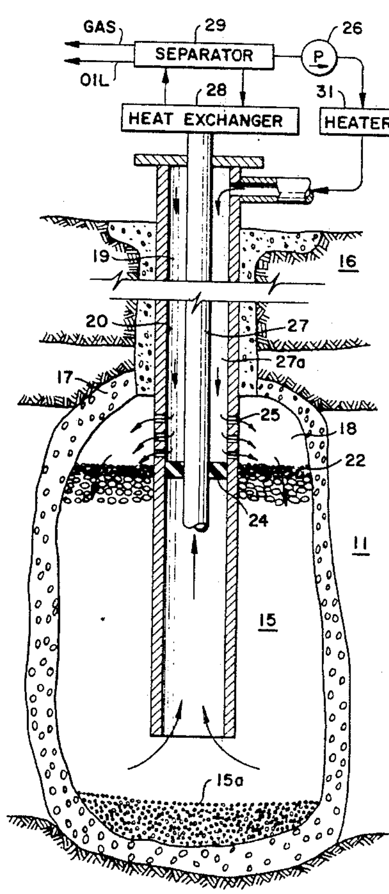
Primary Examiner—Stephen J. Novosad
Attorney—J. H. McCarthy and Louis J. Bovasso

ABSTRACT: In a process for producing shale oil from a subterranean oil shale formation by controlled in situ combustion in a cavern that contains a mass of fracture-permeated oil shale and is located within an oil shale formation, the oil shale is preheated with hot aqueous liquid to exfoliate the pieces of oil shale to cause a reduction in their particle size and improve the distribution of permeabilities and surface area-to-volume ratios within the cavern prior to the initiation of underground combustion.



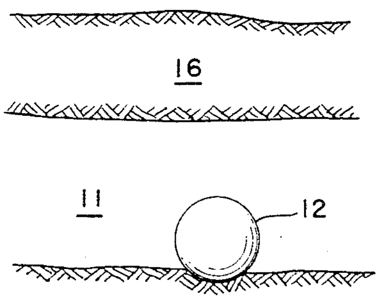


FIG. 1

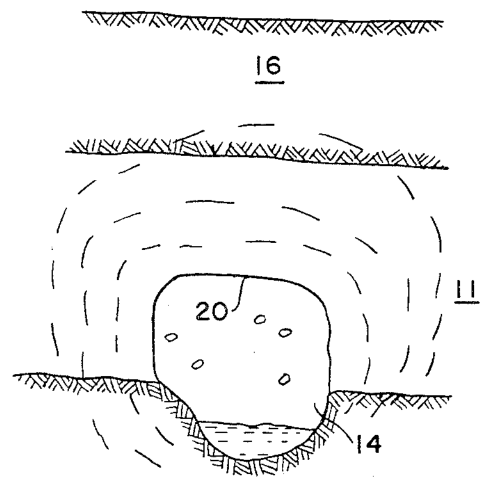


FIG. 2

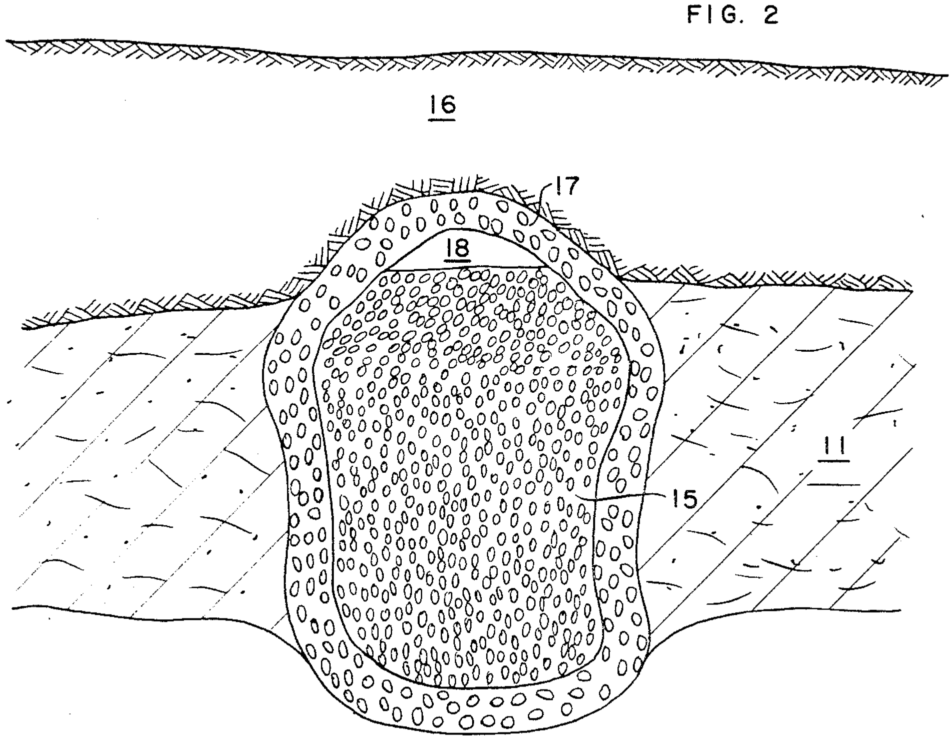


FIG. 3

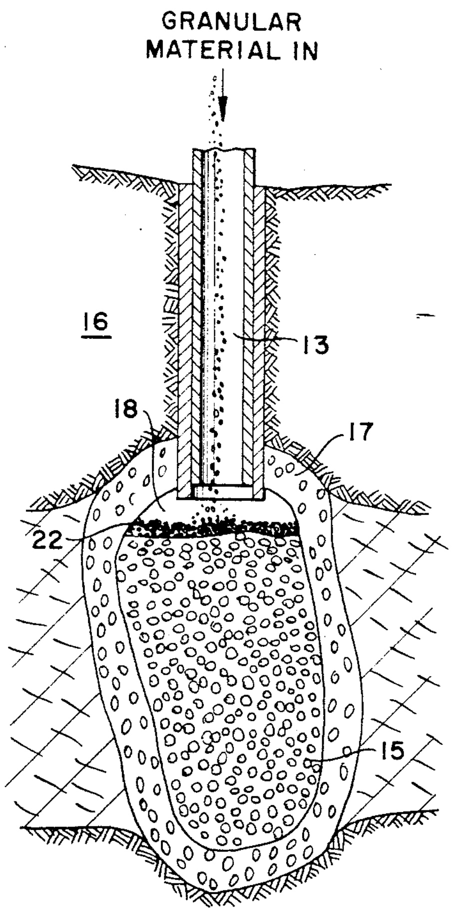

GRANULAR
MATERIAL IN
16
13
18
17
22
15

FIG. 4

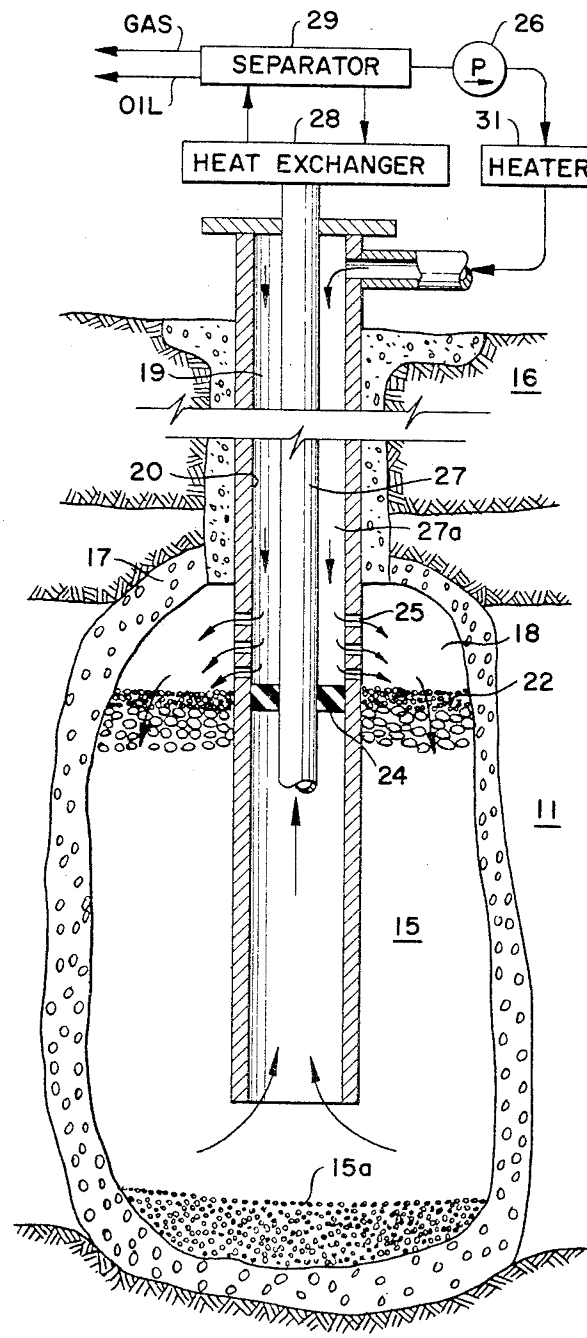

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FIG. 5

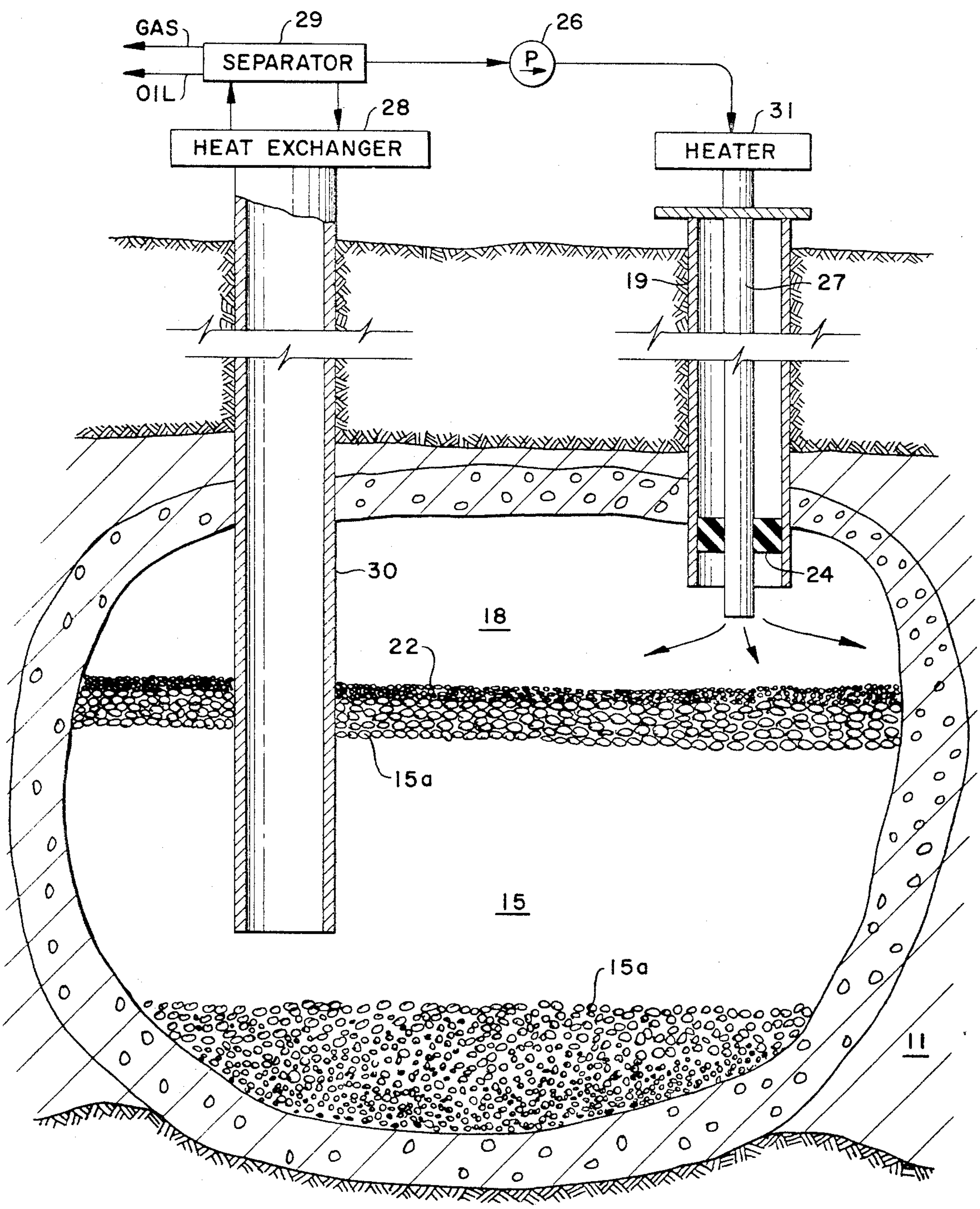
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FIG. 6

METHOD FOR PRODUCING SHALE OIL FROM AN EXFOLIATED OIL SHALE FORMATION

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to an improved in situ combustion method of producing shale oil from a subterranean oil shale formation by normalizing the permeabilities of the flow paths between the pieces of shale in a rubble-filled cavern by exfoliating and reducing the particle size of at least a portion of the pieces prior to the initiation of an in situ combustion.

2. Description of the Prior Art

The use of contained nuclear explosions has been proposed in subterranean oil shale formations in an attempt to break up the oil shale formation so that shale oil can be recovered from the rubbled zone by known techniques, such as in situ retorting.

Experience has shown that when a relatively high energy device, such as a nuclear bomb, is exploded within a subterranean earth formation, an almost spherical cavity filled with hot gases is formed. This cavity expands until the pressure within the cavity equals that of the overburden. On cooling, the roof of the cavity collapses since, generally, it cannot support itself, and a so-called "chimney" develops. Chimney growth ceases when the rock pile substantially fills the cavity, or, a stable arch develops. In both cases, a substantially void space is formed below the overburden and above the rubble contained within the chimney. Surrounding the chimney is a fractured zone which results from the shock of the nuclear explosion.

A zone or chimney of fragmented oil shale resembles an oil reservoir in the sense that each is a permeable formation that contains combustible organic material. A combustion front can be advanced through such a formation by injecting an oxygen-containing fluid such as air. The fragmented oil shale differs from an oil reservoir in having no matrix permeability and having relatively high, and widely varying, permeabilities in the channels that are formed by the interstices between the rock fragments,

In an oil reservoir in which the rock matrix is permeable, an efficient production of oil can often be attained by a dry, forward combustion process in which the combustion-supporting fluid is a gas such as air, and the combustion front is advanced in the direction of the air flow. The combustion generates hot combustion products that heat the oil, reduce its viscosity and displace most of it ahead of the combustion front. In some oil reservoirs, some advantage is provided by injecting a combustion-supporting fluid that contains an aqueous liquid; but such a use of an aqueous liquid is not essential, and it is avoided wherever its use involves problems such as gravity layover of the combustion front, damage to the reservoir formation, etc.

A subsurface detonation of a relatively high energy explosive device, such as a nuclear bomb, is a desirable method of forming a vertically extensive zone of fragmented oil shale or rubble within a subterranean oil shale formation. As discussed hereinabove, the underground nuclear detonation tends to form a "chimney" of rubble, *i.e.*, a vertically extensive cylindrically-shaped zone having a void space at the top. It has been suggested, as for example, in a U.S. Pat. No. 3,113,620, to Hemminger, to produce shale oil from a chimney of rubble by igniting the hydrocarbons at the top of the fragmented zone and injecting a combustion-supporting fluid near the top of the fragmented zone and advancing a combustion front down through the zone while producing oil shale pyrolysis products from near the bottom of the zone. In such a combustion process, in comparison with a combustion drive in an oil reservoir, the proportion of organic material remaining in the combustion zone is greater than that in an oil reservoir while the heat capacity of the rocks in the zone is smaller. The presence of the greater proportion of organic material increases the proportion of combustion-supporting fluid that tends to be

consumed in generating unnecessary heat. As soon as a portion of oil shale has been pyrolyzed, any additional heating of the residue is unnecessary. The proportion of organic material that is left by the pyrolysis of an oil shale is more than is needed to provide the heat used in pyrolyzing the oil shale.

In advancing an underground combustion front, the generation of unnecessary heat may be avoided by incorporating aqueous liquid in the combustion-supporting fluid. The aqueous liquid reduces the temperature and rate of fuel consumption in the combustion zone. Because of the relatively low heat capacity in a fragmented oil shale, the water-to-air ratio of such a combustion-supporting fluid is relatively critical and amounts to about three-fourths as much as required for a viscous oil reservoir.

SUMMARY OF THE INVENTION

The objects of this invention are inclusive of (1) providing an improved process for initiating and conducting an underground combustion in a subterranean oil shale, (2) providing a process for normalizing the effective permeabilities of the interstices between chunks or fragments of oil shale that have been displaced into a cavern or cavity within a subterranean oil shale formation while exfoliating the chunks or fragments and increasing the surface-to-volume ratio of the oil shale within the cavern or cavity, and (3) providing an improved process for preheating and igniting the organic material exposed along the surfaces of a fracture-permeated mass of oil shale in a cavern or cavity within a subterranean oil shale formation by a sequence of steps that provides both a relatively low cost preheating and ignition procedure and an exfoliation of the oil shale within the cavern or cavity.

The objectives of this invention are accomplished by (1) forming a cavern that contains a mass of fracture-permeated oil shale within a subterranean oil shale formation, (2) preheating the mass of oil shale by flowing a hot aqueous liquid into and out of the mass until at least a portion of the mass has been heated to at least several hundred degrees Farenheit for at least several days, (3) initiating and supporting an underground combustion within the mass of fracture-permeated oil shale by inflowing a combustion-supporting fluid, and (4) recovering shale oil from the outflowing fluid.

A cavern that contains a mass of fracture-permeated oil shale can be formed within a subterranean oil shale in numerous ways. In one procedure, preferred for use in practicing the present invention, such a cavern is formed by detonating a high energy explosive device within the oil shale formation. Alternatively, such a cavern can be formed by removing a portion of the oil shale formation and fracturing portions of the surrounding formation so that chunks or fragments are displaced into the void left by the removal of the portion of the formation. Particularly suitable procedures for forming a fragment-filled cavern by mining and fracturing techniques are disclosed in U.S. Pat. No. 3,434,757 to Prats on mining oil shale from tunnels which are arranged to facilitate a roof collapse, collapsing the tunnels and producing oil shale by an in situ retorting of the fragments within the collapsed tunnels, and patent application Ser. No. 770,964, filed Oct. 28, 1968 to Beard on solution-mining soluble minerals, such as nahcolite, from layers or deposits within an oil shale formation, fracturing the surrounding formation to displace solid oil shale into the solution-mined caverns and producing shale oil by an in situ retorting of the fragments within and around the cavern. It is desirable that the cavern or cavity that contains a mass of fracture-permeated oil shale contain a fluid-filled portion of space in the order of at least about 10 percent of the total volume of the cavern, in order to provide solid-free space into which solid materials can be displaced, during the exfoliation of the oil shale, without necessitating a compressing or lifting of portions of the surrounding oil shale formation.

In preheating the mass of fracture-permeated oil shale within such a cavern, the hot aqueous liquid which is flowed into and out of the mass is preferably heated at a surface location or within the borehole of a well. In a preferred procedure, the water is preferably softened to the extent required to prevent thermally-induced scale formation, heated in a water heater devoid of a steam drum or separator, and pumped through a well into the mass of oil shale. The rate of flow and the extent of heating is preferably adjusted to provide a mixture of water and steam that becomes substantially completely liquid by the time it reaches the mass of oil shale. Where the water available at the well site is relatively hard, the heating can advantageously be accomplished by means of the equipment and techniques described in U.S. Pat. No. 3,193,009 on generating and utilizing a "low-grade" " steam, with the steam generator being adjusted to provide a mixture of steam and brine that becomes substantially completely liquified by the time it reaches the oil shale being treated.

The preheating can be continuous or intermittent but should be extended over a time such that, at least near the point of injection, the mass of fracture-permeated oil shale is heated to a temperature of at least several hundred degrees Farenheit (preferably to about 400 or 500°F.) for at least several days (preferably for at least a week or more). We have discovered that in such a situation, in which solid portions of the oil shale are relatively free to move, such a contacting of an oil shale with a hot aqueous liquid causes a relatively extensive exfoliation of the oil shale. Heretofore it was believed to be necessary to contact portions of such an oil shale with relatively expensive special oil solvent materials, such as the mixture of low molecular weight alkyl monocarboxylic acid and hydrocarbon solvents described in U.S. Pat. NO. 3,322,194, in order to cause a "rotting" or otherwise parting of the oil shale formation along its planes of weakness. We have found that within a cavern that contains a mass of fracture-permeated oil shale, the present type of pretreatment with hot aqueous liquid causes the oil shale to become exfoliated into a mass of relatively fine particles that are surrounded by relatively uniformly permeable interstices and have a relatively high ratio of surface area to volume. For example, in an experiment simulating a preheating of a fracture-permeated portion of an oil shale formation, a solid block having a volume of several cubic feet of 23 gallon per ton (Fisher Assay) oil shale was mounted within a pressure-tight, thermally-insulated chamber. Hot water was circulated through the chamber at temperatures increasing from 300°F. to 520°F., under pressures of from about 900 p.s.i.g. to 950 p.s.i.g., over a period of 13 days. Temperatures of about 500°F. were maintained during the last 2 days. Initially, after 1 day of heating at 300°F. the chamber was opened, and the block of oil shale was found to contain numerous fractures extending throughout the exposed portion. The shale block was cemented to the top of the chamber so that a fluid flow path existed along a bottom face located about 4 inches above the bottom of the chamber. After the 13 day heating, the block of oil shale was exfoliated, or broken up into fragments having average dimensions of 1 to 2 inches throughout a portion amounting to about 30 percent of the total volume of the block.

The circulation of hot aqueous liquid through a fracture-permeated mass of oil shale normalizes the permeability of the mass. The flow rate of the hot liquid is highest where the initial permeability is highest. Since the rate of exfoliation is highest where the flow rate is highest, the pieces of oil shale that were initially large enough to be separated by the channels of highest permeability are the first to be reduced to smaller particles separated by channels of lower permeability. such a normalization of the permeability tends to ensure that all portions are uniformly contacted by fluid flowing through the mass of particles, and the creation of a high ratio of surface area-to-volume, due to the reduction in the size of the particles, tends to ensure that all internal portions are heated at about the same rate to a temperature at which the kerogen components are pyrolyzed to shale oil.

The preheated fracture-permeated oil shale material can be ignited and swept by a combustion front, to pyrolyze its kerogen components to shale oil materials that are recovered from produced fluids, by substantially any procedures for causing the hot oil shale material to be contacted with a relatively easily oxidizable material along with a combustion-supporting fluid. Particularly suitable techniques for ensuring a prompt ignition of such an underground combustion, by injecting a readily oxidizable material preceded by a combustion supporting fluid, are described in U.S. Pat. No. 2,863,510. Particularly suitable techniques for advancing such an underground combustion front through a permeable earth formation and recovering oil from the produced fluids are described in U.S. Pats. such as Nos. 3,196,945, 3,208,519, etc. Where the oil shale material is relatively rich and the preheating of the mass of fracture-permeated oil shale is adjusted to provide a relatively high temperature adjacent to the point of fluid injection, the ignition can be accomplished by simply terminating the injection of the hot aqueous liquid and starting the injection of a combustion-supporting fluid, such as compressed air.

Where the cavern which contains a mass of fracture-permeated oil shale material is a generally vertical, nuclear detonation "chimney", the application of the present process can advantageously be preceded by initially depositing a layer of granular material along or near the top of the mass in the manner described in the copending patent application, Ser. No. 768,666, filed Oct. 18, 1968.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a vertical cross-sectional view of an oil shale formation prior to detonating a relatively high energy explosive device within the formation;

FIG. 2 is a vertical cross-sectional view of the oil shale formation of FIG. 1 after the explosive device has been detonated;

FIG. 3 is a vertical cross-sectional view of the final rubble zone created by detonating the explosive device of FIG. 1;

FIG. 4 is a vertical sectional view of the rubble zone of FIG. 3;

FIG. 5 is a vertical sectional view of an oil recovery process applied to the oil shale formation of FIG. 1; and

FIG. 6 is a vertical sectional view of an alternate oil recovery process applied to the oil shale formation of FIG. 1.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 shows a subterranean oil shale formation 11 having a relatively high energy explosive device 12 located within the formation 11. The device 12 may be either nuclear or non-nuclear; if a nuclear device is detonated within the oil shale formation 11, a strong shock wave from the nuclear device begins to move radially outwardly, vaporizing, melting, crushing, cracking and displacing the oil shale formation 11. After the shock wave has passed, the high pressure vaporized material expands, and a generally spherical cavity 14 (FIG. 2) is formed which continues to grow until the internal pressure is balanced by lithostatic pressure. The cavity 14 persists for a variable time depending on the composition of the oil shale formation 11. The cavity roof 20 then collapses to form a "chimney" 15 (FIG. 3). Collapse progresses upwardly until the volume initially in cavity 14 is distributed between the fragments of the oil shale of formation 11. The size of the substantially cylindrical rubble zone, *i.e.*, chimney 15, formed by the collapse of the cavity 14, may be estimated from the fact that the initial cavity 14 (FIG. 2) expands until the pressure within the cavity is about equal to the lithostatic pressure.

A zone of permeability 17 within and around the fragmented oil shale formation is formed surrounding the chimney 15 as can be seen in FIG. 3. If desired, the permeability of the zone 17 may be increased by surrounding the primary explosive device of FIG. 1 which forms the central cavity with a plurality of devices of lesser explosive energy, subsequently detonated in the manner disclosed in a copending application to Closman et al. Ser. No. 653,139, filed July 13, 1967, and now U.S. Pat. No. 3,448,801

A subsequently void space **18** is formed at the top of the chimney of rubble **15**. When used throughout this specification, the terms "fragmented zone" and "fragmented zone of rubble" refer to the chimney **15** or any other rubbled or fracture-permeated zone formed by the explosion of a relatively high energy explosive device.

Where desirable in order to normalize the effective permeabilities of chimney **15** before injecting hot aqueous fluid to preheat the fracture-permeated mass within the chimney, a layer **22** of granular material (FIG. **4**) is deposited across an upper portion of the chimney **15** at a depth between those at which fluids are to be injected and produced from chimney **15** as will be discussed further hereinbelow. This may be accomplished by extending a well **13** into communication with the void space **18** at the top of chimney **15** and injecting the granular material from an external source (not shown) through well **13** and across, for example, the upper portion of the rubble within chimney **15**. The permeability of the layer **22** of granular material is adjusted to one that is uniform across the chimney **15** and is low relative to the average permeability with the chimney **15** in a manner to be discussed further hereinbelow.

Referring now to FIG. **5**, a preferred arrangement for producing shale oil from the fragmented zone of FIG. **4** is illustrated. A well **19** is extended to the bottom of the chimney **15** thereby establishing communication with the fracture-permeated oil shale or rubble **15*a***. Well **19** is preferably drilled into the bottom of the rubble **15*a*** within chimney **15** while the rubbled zone is hot, or at least warm, from the aforementioned explosion. well **19** may be cased at least along the portion traversing the overburden **16** and the oil shale formation **11**, as at well casing **20**, with casing **20** cemented therein as is well known in the art. Well **19** is equipped with a tubing string **27** and an annulus **27*a*** between the tubing string and casing **20**. These form well conduits for injecting fluid through the borehole opening above packer **24** and through openings **25** formed in well **19**. The openings **25** may be formed by perforating means well known in the art, as for example, a bullet or jet-type perforator. The injected fluid passes into the void space of the upper portion of chimney **15** and down through the layer **22**, where such a layer is used, into the rubble **15*a*** and is produced through tubing string **27**.

In practicing this invention the oil shale in the chimney is preheated by circulating hot aqueous fluid through the conduits **27** and **27*a*** and rubble **15*a***. An in situ combustion is then initiated and supported by a similar circulation of combustion-supporting fluid, with displaced and/or combustion-produced fluid that contains shale oil being outflowed from the rubble **15*a***.

The combustion-supporting fluid comprises a mixture of combustion-supporting gas, such as air or oxygen, and aqueous liquid, such as water, and is injected in a manner that distributes the liquid substantially uniformly across the top of the chimney **15**. Such a distribution of the aqueous liquid may be accomplished by mechanical means well known in the art, such as by fixed or rotating deflectors or jets (not shown) which disperse the water and air mixture, for example, over the surface of a granular layer **22**. The injection of air mixed with water that is mechanically distributed throughout the areal extent of the void space **18** within chimney **15** limits the combustion temperature and oxygen consumption of the combustion front. Because of the relatively high proportion of organic fuel that may remain in chimney **15** after the organic components have been pyrolyzed, the injected air must be mixed with enough water to limit the amount of oxygen consumption.

Alternatively, water and air, again for example, may be injected over layer **22** in the form of a foam. For example, such a foam may be preferably formed by dispersing about 0.2 percent by weight of a foaming agent in water and dispersing the air in the aqueous phase in a proportion of about 2 cubic feet of aqueous phase per 1,000 standard cubic feet of air.

A suitable foaming agent is "Adofoam," a liquid mixture of anionic surface-active agents, manufactured by Conoco Petrochemicals of Houston, Texas. Nonionic surfactants and mixtures of anionic–nonionic surfactants may also be used.

As the combustion front advances down the chimney **15**, oil shale pyrolysis products are recovered at the bottom of well **19**. These products pass up through tubing string **27** where the shale oil and gas entrained in the recovered products passes through a heat exchanger **28** and into a separator **29**. At this point, the shale oil and gas components are separated as is well known in the art. The recovered combustion-supporting gas may be recirculated from separator **29** through pump **26** and heater **31** as is also well known in the art.

Referring now to FIG. **6**, wherein like numerals refer to like parts of FIG. **5**, an alternate process for recovering shale oil from chimney **15** is shown. In place of the same well being opened into both the void space **18** and the bottom of chimney **15**, a well **30**, independent of well **19**, is opened into the lower end or bottom of chimney **15**. Thus, the circulating preheating and combustion-supporting fluids are injected through tubing string **27** and, preferably, onto a granular layer **22** disposed across the upper portion of the rubble **15*a*** within chimney **15**. As the combustion front moves downwardly in the manner discussed hereinabove, oil shale pyrolysis products are recovered up well **30** at its lower end adjacent the bottom of rubble **15*a***. Again, conventional equipment and techniques, such as heater **31**, pump **26**, separator **29** and heat exchanger **28**, may be used for pressurizing, heating, injecting, producing and separating components of the oil shale-pyrolysis products circulating out of the chimney **15**.

In a rubble-filled nuclear chimney such as chimney **15**, the interstices between the fragments of oil shale have widely different effective permeabilities. A fluid-filled void, such as void space **18**, usually exists above the rubble **15** and tends to create an essentially constant pressure differential between any portion of the upper part of the fragmented zone (*i.e.*, the chimney of rubble) and the point at which fluid is withdrawn from near the bottom of the chimney. Fluid injected into the upper portion and withdrawn from near the bottom of the chimney tends to finger through the fragmented oil shale by flowing rapidly through some portions and bypassing others. Such an injection of combustion-supporting fluid causes a combustion front to advance rapidly along some highly permeable channels and bypass other less permeable portions of the fragmented zone. During such a nonuniform advance, conductively transported heat causes the pyrolysis of the oil shale in the bypassed portions, but the pyrolysis products are burned as they flow into zones in which combustion is occurring. This results in an inefficient process that tends to consume much air and organic material while producing relatively little shale oil. The exfoliation of the oil shale pieces into uniformly small pieces normalizes the times required to pyrolize the kerogen near the center of the pieces and reduces the fluid fingering or bypassing tendencies.

If desired, the volume of the permeable zone may be increased by opening and/or enlarging perforations or fractures into the oil shale in and around the fractured zone **17** surrounding the void space **18**. In respect to circulating fluid between the void space **18** and a lower portion of the rubble **15*a*** this provides a flow path inclusive of such openings and the fractured zone **17**. The tendency for the inflowing fluid to flow latterally outward into such openings before or during a downward flow through rubble **15*a*** (toward the location from which the outflowing fluid is produced) is enhanced by the flow resistance imparted by a layer of relatively low permeability, such as layer **22**.

The present process of forming a rubble-containing cavern within a subterranean oil shale formation and preheating it by circulating hot aqueous liquid through the cavern and the rubble can advantageously be used in shale oil production processes in which the kerogen is thermally and/or chemically converted to shale oil by contacting it with a hot kerogen conversion fluid other than hot fluid products of an in situ combustion. For example, the preheating can be followed by the initiation of a conversion of kerogen to shale oil by the inflowing of a hot oil solvent and the recovering of shale oil from the outflowing fluid. Volatile hydrocarbons and/or mixtures of such hydrocarbons and polar compounds such as phenols, halogenated organic compounds etc. can be used as the hot oil solvent. In such a shale oil conversion process, the present type of preheating provides a significant reduction in the amount of solvent required. During the preheating, a volume of fluid that is greater than the pore space of the rubble-containing cavern must be heated and circulated through the cavern. In the present process, such a preheating uses only a relatively low cost aqueous fluid, which can be economically heated by means of presently available equipment and techniques. Since oil solvents tend to be lost, due to their thermal reactions and subterranean leakage, the hot water preheating saves the amount that would be lost in reaching a temperature up to the critical temperature of the aqueous fluid or at least up to the vapor pressure of the aqueous fluid at the highest pressure it is desirable to maintain within the cavern. The hot water preheating also normalizes the permeability and improves the ratio of surface area to volume within the cavern so that when the hot solvent is circulated it is circulated through a mass of fracture-permeated oil shale that has been preconditioned for the most efficient conversion of kerogen to oil shale.

We claim:

1. A process of recovering shale oil from a subterranean oil shale, which process comprises:

extending at least two well conduits into fluid communication with a cavern which contains a mass of fracture-permeated oil shale and is located within a subterranean oil shale formation;

preheating said mass of fracture-permeated oil shale by circulating hot aqueous liquid through said well conduits and said oil shale until at least a portion of the oil shale has been heated to at least several hundred degrees Fahrenheit for at least several days;

initiating and supporting an underground combustion within said mass of fracture-permeated oil shale by inflowing a combustion-supporting fluid into the preheated oil shale through at least one well conduit, with fluid being outflowed through at least one other well conduit; and

recovering shale oil from the outflowing fluid.

2. The process of claim 1, in which: said cavern that contains a mass of fracture-permeated oil shale is a nuclear detonation chimney; and at least one of said well conduits is extended into fluid communication with the void space near the top of said chimney and at least one other well conduit is extended into fluid communication with said fracture-permeated oil shale material near the bottom of said chimney.

3. The process of claim 1, in which:

said cavern that contains a mass of fracture-permeated oil shale is a generally horizontal cavern into which pieces of the surrounding oil shale formation have been displaced; and

said well conduits are extended into fluid communication with said cavern through at least two wells.

4. The process of claim 1 in which said combustion-supporting fluid comprises a mixture of a gas that contains gaseous oxygen and an aqueous fluid.

5. A process of recovering shale oil from a subterranean oil shale formation, which process comprises:

extending at least two well conduits into fluid communication with a cavern that contains a mass of fracture-permeated oil shale and is located within a subterranean oil shale formation;

preheating said mass of fracture-permeated oil shale by circulating hot aqueous liquid through said well conduits and said oil shale until at least a portion of the oil shale has been heated to a temperature of at least several hundred degrees Fahrenheit for at least several days;

conducting an in situ conversion of the kerogen in said oil shale to shale oil by inflowing a hot kerogen-conversion fluid into the preheated oil shale through at least one well conduit, with fluid being flowed out through at least one other well conduit; and

recovering shale oil from said outflowing fluid.

6. The process of claim 5 in which said kerogen-conversion fluid consists essentially of at least one fluid hydrocarbon.