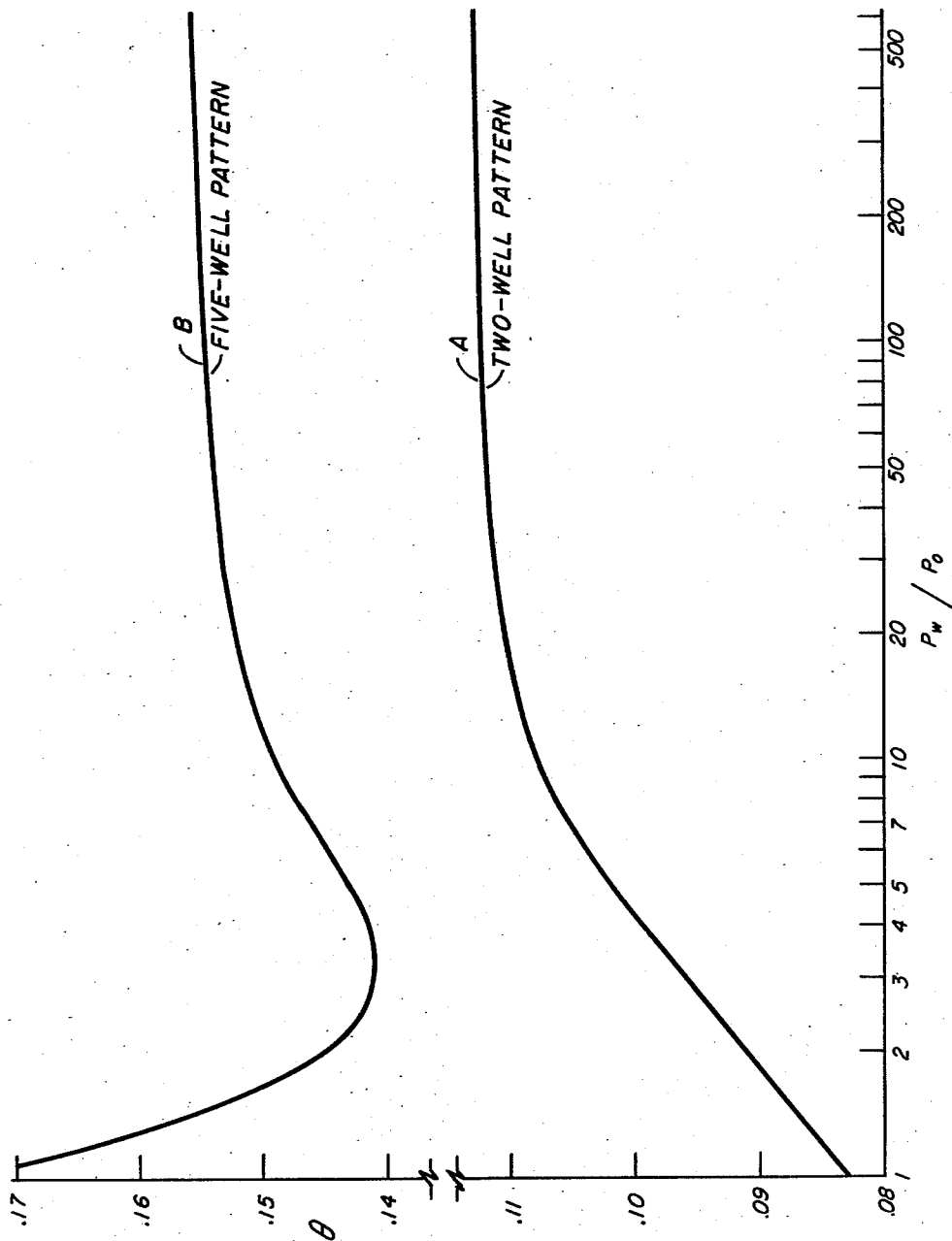


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DETERMINATION OF THE LOCATION OF THE FLAME
FRONT IN A SUBTERRANEAN FORMATION
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DETERMINATION OF THE LOCATION OF THE FLAME FRONT IN A SUBTERRANEAN FORMATION

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This invention relates to the recovery of hydrocarbon materials from a subterranean formation and relates more particularly to the recovery of such materials by the method involving combustion in place of a portion of the hydrocarbons in the subterranean formation.

It has been proposed to recover hydrocarbon materials from a hydrocarbon-containing subterranean formation by a method which involves combustion of a portion of the hydrocarbons within the formation. In this method, combustion supporting gas is injected into the formation through an input well and combustion of hydrocarbon within the formation is initiated by suitable means. The formation is provided with a single output well, or is provided with four output wells, each of the four output wells spaced 90° from each other on a circle having the input well as its center, and, as the flow of combustion supporting gas to the formation is continued, a flame front migrates from the input well to the output well or output wells. Combustion gases, oil, and distillation and viscosity breaking products of the hydrocarbon migrate in advance of the flame front to the output well or output wells from which they are removed to be treated for recovery of the desired valuable hydrocarbon material or other constituents. The heat of the fluids migrating in advance of the flame front strips the hydrocarbon-containing formation of water and the greater portion of the hydrocarbon leaving behind a carbonaceous deposit. This carbonaceous deposit is essentially the fuel consumed in the process and the flame front migrating from the input well to the output well or wells is the zone of combustion progressively moving through the carbonaceous deposit. In carrying out the combustion process, it is often necessary or desirable to determine the location of the flame front with respect to its distance between the input well and the output well or one or more of the output wells. Thus, to estimate the yield of hydrocarbon materials, to estimate the time of arrival of the flame front at an output well, to control the rate of advance of the flame front, or to effect other purposes, knowledge of the location of the flame front is essential.

It is the principal object of this invention to provide a method for determining the location of a flame front in a subterranean formation wherein combustion has been effected for the purpose of recovering hydrocarbon materials. Other objects of the invention will become apparent from the following detailed description thereof.

In accordance with the invention, there is provided a method for the location of the flame front in a subterranean formation between an input well leading to the formation and an output well leading from the formation which comprises as essential steps thereof the determination both prior and subsequent to the initiation of combustion within the formation of the time required for gas to travel through the formation between the input well and the output well and the determination of the porosity of the formation.

The invention is based upon the discovery that the

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time required for a gas to travel through the formation between an input well leading to the formation and an output well leading from the formation is dependent upon the gas saturation within the formation. By gas saturation is meant the fraction of the pore volume of the material of the formation which is occupied by gas. Passage of the flame front through the formation removes the carbonaceous deposit and since the heat of the fluids migrating in advance of the flame front strips the formation of the water and the greater portion of the hydrocarbons, the gas saturation in the portion of the formation traversed by the flame front is unity, i. e., the entire pore volume of the material of the formation is occupied by gas. Thus, the passage of the flame front through the formation changes the time required for a gas to travel through the formation between the input well and an output well, and from the change in time the location of the flame front between the input well and the output well can be determined.

The gas saturation in a subterranean formation prior to passage of the flame front therethrough can be expressed as follows:

$$S = \frac{2.339Qt}{\phi h L^2 (P_w + P_o) \theta} \quad (1)$$

where

S = the gas saturation, fraction of the pore volume of the material of the formation occupied by gas

Q = rate at which gas is injected into the formation through the input well, standard cubic feet per hour
 t = time required for gas to travel through the formation between the input well and the output well, hours

ϕ = porosity, fraction of the bulk volume of the material of the formation occupied by pore space

h = thickness of the formation, feet

L = distance between the input well and the output well, feet

P_w = pressure at which the gas is injected into the input well, pounds per square inch

P_o = pressure at which the gas leaves the output well, pounds per square inch

θ = dimensionless time factor related to P_w and P_o and the well pattern

The time required for gas to travel through the formation between the input well and an output well, all other factors being equal, will be a function of the ratio of the pressure at which the gas is injected into the input well, P_w , and the pressure at which the gas leaves the output well, P_o . The time will also be a function of the output well pattern since the number of the output wells and their spatial positions with respect to the input well will govern the area of the formation swept by the gas traveling through the formation from the input well. This factor representing the ratio of the pressure at which the gas is injected into the input well and the pressure at which the gas leaves the output well and the output well pattern appears in the above equation as the dimensionless time factor θ . Its value for various ratios of the pressure at which the gas is injected into the input well and the pressure at which the gas leaves the output well prior to the initiation of combustion has been mathematically determined by me from basic equations of fluid flow in porous media and is given in the accompanying figure. In the figure, the abscissa is the ratio, P_w/P_o , of the pressures and the ordinate is the dimensionless time factor, θ . Curve A gives the variation in the value of θ with the variation in the value of P_w/P_o for the case where the formation contains one output well, i. e., a two-well pattern, and curve B gives the same information for the case where the formation contains four output wells spaced 90° from each other on a circle having the

input well as its center, i. e., a five-well pattern. From either curve A or B, depending upon the well pattern, the value of θ can be determined for each ratio P_w/P_o of the pressures. The values of the ratio P_w/P_o given in the figure are between 1 and 500 which includes all values ordinarily encountered in practice. For higher values of the ratio P_w/P_o greater than 500, the value of θ may be taken as 0.113 for a two-well pattern and as 0.156 for a five-well pattern.

Subsequent to the initiation of combustion, the value of the dimensionless time factor, θ , is obtained from Equation 1 and is expressed as follows:

$$\theta = \frac{2.339Qt}{\phi h L^2 (P_w + P_o) S} \quad (2)$$

In Equation 2, the value of S is the value prior to initiation of combustion in the formation.

By the method of the invention, the location of the flame front along a straight line between the input well and the output well in a two-well pattern or any particular output well in a five-well pattern can be determined at any time during combustion within the formation. For this determination there is measured, prior to initiation of combustion within the formation, the time required by gas to travel through the formation between the input well and the particular output well. Measurement of this time is effected by injecting into the formation through the input well any gas which is capable of traveling through the formation and from which a gas component is obtained whose arrival at the particular output well will be detectable and measuring the time between the entrance of the gas into the formation and the first appearance of the detectable gas component at the particular output well. This gas may be air or other combustion supporting gas to be employed for maintaining combustion within the formation, if its arrival at the output well is detectable, or this gas may be some gas other than the combustion supporting gas. The detectable gas component may be a component originally present in the gas or may be a component produced therefrom by reaction within the formation. The time may be conveniently measured, if detection of the arrival at the particular output well of a detectable gas component obtained from the combustion supporting gas is difficult or undesired, involves by a procedure which injecting into the formation the combustion supporting gas, adding to the combustion supporting gas another gas which will accompany the combustion supporting gas through the formation and from which a gas component is obtained whose arrival at the particular output well is detectable, and measuring the time between the injection of this gas, hereinafter termed a tracer gas, and the first appearance of the detectable gas component at the particular output well.

The time, t , for gas to travel through the formation between the input well and the particular output well having been measured, its value is substituted in Equation 1. The rate at which the gas is injected into the formation through the input well and the pressures at the input well and the particular output well will be known or are readily measurable. These values are substituted in Equation 1 for Q , P_w , and P_o , respectively. From the ratio P_w/P_o , the value for θ is obtained from the accompanying figure and this value is also substituted in the equation. Additionally, the distance between the input well and the particular output well, as well as the thickness of the formation, will be known or is readily measurable and these values of L and h , respectively, are substituted in the equation. The right hand side of Equation 1, therefore, will be complete except for the value of the porosity ϕ .

Knowing the porosity of the formation, the gas saturation may be calculated from Equation 1. It is true that knowing the gas saturation, the porosity may be calculated from Equation 1 and that both the porosity and the gas saturation may be measured on a core sample taken from

the formation. However, since gas saturation is expressed as the fraction of the pore volume of the material of the formation occupied by gas, measurement of gas saturation also involves measurement of pore volume, or porosity. But of greater significance is the fact that the measurement of gas saturation of a core sample is unreliable because of difficulties in preventing loss of liquid from the core sample, contamination of the core sample with liquids within the bore hole during the sampling operation, and loss of liquid from the core sample with change of pressure upon removal from the formation. Therefore, from the standpoint of accuracy the porosity of the core sample is measured. For the same reasons, the time required for gas to travel through the formation between the input well and the particular output well before combustion is initiated in the formation is measured, even though it could be calculated from Equation 1 by employing a measured value of the gas saturation and the measured value of the porosity.

The porosity of the core sample may be measured in any known manner. Suitably, the core sample after being cleaned and dried is placed in a chamber and subjected to a known pressure of a gas. The gas pressure is thereafter reduced a known amount and the volume of gas leaving the core sample as a result of the reduction in pressure is measured. Knowing the volume of gas leaving the pore spaces of the core sample and the reduction in pressure, the volume of the pore spaces, or the porosity, can be calculated employing the gas law.

The value for each of the factors having been substituted in Equation 1, the value of S is then calculated. The value of S need be determined with respect to only one output well where a five-spot well pattern is employed. However, in order to minimize errors in determining the location of the flame front between the input well and any of the other output wells arising from possible differences in the value of the gas saturation, it is preferred to determine the value of S with respect to each of the output wells.

Following determination of the gas saturation, initiation of combustion is effected within the formation. Thereafter, combustion supporting gas is injected into the formation to maintain the combustion and the flame front migrates into the formation from the input well. At any time subsequent to initiation of combustion within the formation, measurement of the time required for gas to travel through the formation between the input well and any output well will locate the position of the flame front on a straight line between the input well and the particular output well. Measurement of the time required for gas to travel through the formation between the input well and any output well subsequent to the initiation of combustion is effected by adding to the combustion supporting gas being injected into the input well any gas which will accompany the combustion supporting gas through the formation and from which a gas component is obtained whose arrival at the output well will be detectable, i. e., a tracer gas, and measuring the time between the entrance of this gas into the formation and the first appearance of the detectable gas component at the output well. The detectable gas component may be, as before, a component present in the gas injected into the input well or may be a component produced therefrom by reaction within the formation.

Helium is preferred as the tracer gas. However, radon or neon may be employed. The tracer gas added to the combustion supporting gas subsequent to initiation of combustion may be the same or may be a different tracer gas than the one employed, if such is the case, prior to initiation of combustion within the formation.

Addition of the tracer gas to the combustion supporting gas, either prior or subsequent to the initiation of combustion, may be accomplished by any suitable means. For example, the tracer gas may be admixed with combustion supporting gas in a tank, a pressure may be im-

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posed on the mixed gas in the tank above the pressure at which combustion supporting gas is being injected into the formation, and the mixed gas may be bled into the stream of combustion supporting gas. The rate at which the mixed gas is bled into the stream of combustion supporting gas may vary and will depend upon the concentration of tracer gas in the mixed gas and the rate of flow of the combustion supporting gas. Generally, the tracer gas may be admixed in the tank with the combustion supporting gas in a volume ratio of about 1 to 10 and the rate at which the mixed gas is added to the stream of combustion supporting gas should be such that the concentration of the detectable gas component in the mixture entering the input well will be sufficiently high to render the component readily detectable when arriving at the output well. The addition of about one standard cubic foot of tracer gas in admixture with about ten standard cubic feet of combustion supporting gas to the stream of combustion supporting gas over a period of about 30 seconds has been found to be satisfactory.

Detection of the appearance of the detectable gas component at the output well for the purpose of determining the time required for travel of gas through the formation may be made by any suitable procedure depending upon the detectable gas component. Where helium is employed, the detectable gas component will be helium and periodic analysis of the gas entering the output well for the presence of the added helium may be made. A suitable analytical procedure for helium comprises taking at short time intervals samples of the gas entering the output well from the formation, the time of taking each sample being noted, and contacting the samples with charcoal at liquid nitrogen temperatures whereby all gas except helium is absorbed, and noting the volume of unabsorbed gases. The presence of a volume of unabsorbed gas in any sample greater than the volume of helium that would be expected from the quantity naturally present in the combustion supporting gas indicates the presence of the added helium. Analysis for neon at the output well, where neon is used as the tracer gas, may be similarly made. Where radon is employed, radon will be the detectable gas component and its presence in the gas entering the output well may be determined by measurement of the radioactivity of this gas, a Geiger-Mueller counter, a scintillation counter, a proportional counter, or other type of radioactivity measuring instrument being employed for this purpose. Knowing the time the tracer gas enters the formation through the input well and knowing the time that the detectable gas component enters the output well from the formation, a value of t subsequent to initiation of combustion becomes known.

The values for Q , P_w , and P_o are also determined.

During the measurement of the time, t , for gas to travel through the formation between the input well and the output well, it is contemplated that the values for Q , P_w , and P_o shall remain substantially constant. However, variations in these values during the measurement of the time, t , may occur. In such cases, the values for Q , P_w , and P_o to be employed in the equations should be integrated values taken over the period of time required by the gas to travel between the input well and the output well.

The location of the flame front on a straight line between the input well and the particular output well is given by the following equation:

$$FFL = \frac{\theta_2}{\theta_1} S \quad (3)$$

where

FFL = the flame front location expressed as the fraction of the total distance on a straight line from the input well to the particular output well

θ_1 = the dimensionless time parameter employed in Equation 1 for determining S and obtained from the figure

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for the ratio of P_w/P_o employed prior to initiation of combustion

θ_2 = the dimensionless time parameter given by Equation 2, and

S = the gas saturation of the formation prior to initiation of combustion as determined from Equation 1

The value of θ_1 and S being known, the location of the flame front is determinable from Equation 3 upon determining θ_2 . This latter value is obtained from Equation 2 employing therein the same values for θ , h , and L employed in Equation 1 for determining the value of S and the values for Q , P_w , P_o , and t as determined subsequent to the initiation of combustion. The value of θ_2 being known, this value is substituted in Equation 3 whereby the location of the flame front becomes known.

The following example will be illustrative of the invention.

An input well and four output wells spaced 90° from each other on a circle having the input well as its center, i. e., a five-spot well pattern, were drilled into a petroleum oil formation. Each output well was at a distance of 100 feet from the input well. By logging methods employed in the input well and the output wells, the average thickness of the formation was determined to be 20 feet and from core samples taken during drilling of the wells, the porosity of the material of the formation was determined to be 0.3. Air was injected into the formation through the input well at a constant rate of 10,000 standard cubic feet per hour and the pressure at the input well was 600 pounds per square inch. Pressure at each of the output wells gradually increased but eventually stabilized. At one of the output wells, identified as well No. 1, the pressure stabilized at 100 pounds per square inch. While air was being injected into the input well, the rate and pressure at the input well and the pressure at the output well being as stated, helium was added to the air by admixing one cubic foot of helium with nine cubic feet of air in a tank, pressuring to approximately 650 pounds per square inch, and bleeding within one-half minute the mixed gas from the tank into the air stream entering the formation. Samples of the gas leaving the formation at well No. 1 were thereafter taken at intervals of 15 minutes, the time of taking each sample being noted, and the samples were analyzed for helium by contacting with charcoal held in a chamber provided with a jacket through which liquid nitrogen was circulated. Added helium appeared in the sample taken 20 hours after the helium and air mixture was bled into the injected air stream. The value of t was, accordingly, 20 hours. From the ratio of the pressures at the input well to the pressure at well No. 1, the value of 0.145 was taken from curve B of the figure. The values for Q , t , ϕ , h , L , P_w , P_o , and θ were substituted in Equation 1 as follows:

$$S = \frac{(2.339)(10,000)(20)}{(0.3)(20)(100^2)(600+100)(0.145)}$$

The value of S was accordingly determined to be .0768.

Combustion was then initiated within the formation and air was continuously injected into the formation through the input well to maintain the combustion. After a period of 150 days of continued combustion, it was desired to know the location of the flame front between the input well and well No. 1 and helium was added to the air being injected through the input well, the method of addition and the amount of helium being the same as described above. The pressure at the input well was 400 pounds per square inch at the time of the addition of the helium. The pressure at well No. 1 was 100 pounds per square inch and the rate of injection of air was 10,000 standard cubic feet per hour. Samples were thereafter taken of the gas leaving well No. 1 and were analyzed for helium, the analysis procedure being the same as described above. The time of taking each sample was noted and 70 hours after addition of the helium to the air injected into the input well, added helium ap-

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peared in the gas leaving the output well. The value of t_2 was, accordingly, 70 hours. The values for Q , t , ϕ , h , L , P_w , P_o , and S being known, the value for θ_2 was calculated from Equation 2 as follows:

$$\theta_2 = \frac{(2.339)(10,000)(70)}{(0.3)(20)(100^2)(400+100)(.0768)}$$

The value of θ_2 was, accordingly, 0.711. The values of θ_1 , θ_2 , and S were substituted in Equation 3 as follows:

$$FFL = \frac{0.711}{0.145} .0768$$

and the value of FFL was thus 0.376. The flame front accordingly was located at a distance from the input well along a straight line between the input well and well No. 1 equal to 0.376 of the total distance along a straight line between these two wells.

The invention may be employed in connection with the combustion process for the recovery of petroleum oil from partially depleted subterranean petroleum oil reservoirs where the reservoir energy has decreased to the point that oil is no longer naturally forced to the surface and, particularly to the point that the rate of recovery by pumping is so low as to be uneconomical. The invention may also be employed in connection with the combustion process for the recovery of petroleum oil from a subterranean reservoir wherein the oil has such high viscosity that efficient recovery by water drive or other conventional means cannot be effected. Further, the invention is applicable in connection with the combustion process for the recovery of hydrocarbon materials from earth formations such as tar sands, for example, those existing in the Athabasca region of Canada and elsewhere.

Having thus described my invention, it will be understood that such description has been given by way of illustration and example and not by way of limitation, reference for the latter purpose being had to the appended claims.

I claim:

1. In the process for the recovery of hydrocarbon materials from a subterranean formation containing hydrocarbons and having an input well leading thereto and at least one output well leading therefrom by combustion within said subterranean formation wherein a flame front travels through said subterranean formation from said input well to said output well, the steps comprising measuring the distance between said input well and said output well and the thickness of said subterranean formation, determining the porosity of said subterranean formation, determining prior to initiation of combustion within said subterranean formation the gas saturation of said subterranean formation, passing gas prior to initiation of combustion within said subterranean formation through said subterranean formation between said input well and said output well at a known gas pressure at said input well and at said output well whereby the value of a first dimensionless time factor θ related to the pressure at which said gas is injected into said input well and the pressure at which gas reaches said output well may be taken from the accompanying figure, initiating combustion within said subterranean formation, supplying combustion supporting gas to said subterranean formation through said input well, and measuring at a time subsequent to initiation of combustion in and following supplying of combustion supporting gas to said subterranean formation the time required for gas to travel through said subterranean formation between said input well and said output well at a known rate of injection of said gas into said input well and at a known gas pressure at said input well and at said output well whereby a second dimensionless time factor θ may be determined from the equation:

$$\theta = \frac{2.339Qt}{\phi h L^2 (P_w + P_o) S}$$

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in which equation S is the gas saturation of said subterranean formation prior to initiation of combustion expressed as the fraction of the pore volume of the material of said subterranean formation occupied by gas;

5 Q is the rate at which said gas is injected into said subterranean formation through said input well expressed as standard cubic feet per hour; t is the time required for said gas to travel through said subterranean formation from said input well to said output well expressed as hours; ϕ is the porosity of said subterranean formation expressed as the fraction of the bulk volume of the material of said subterranean formation occupied by pore space; h is the thickness of said subterranean formation expressed as feet; L is the distance between said input well and said output well expressed as feet; P_w is the pressure at which said gas is injected into said input well expressed as pounds per square inch; P_o is the pressure at which said gas reaches the output well expressed in pounds per square inch; and whereby the location of the flame front within said subterranean formation may be determined from the equation:

$$FFL = \frac{\theta_2 S}{\theta_1}$$

25 in which equation FFL is the location of the flame front expressed as the fraction of the distance between the input well and the output well; θ_1 is said first dimensionless time factor; θ_2 is said second dimensionless time factor; and S is the gas saturation of said subterranean formation prior to initiation of combustion expressed as the fraction of the pore volume of the material of said subterranean formation occupied by gas.

2. In the process for the recovery of hydrocarbon materials from a subterranean formation containing hydrocarbons and having an input well leading thereto and at least one output well leading therefrom by combustion within said subterranean formation wherein a flame front travels through said subterranean formation from said input well to said output well, the steps comprising measuring the distance between said input well and said output well, the thickness of said subterranean formation, and two of three terms, (a), (b), and (c), of which three terms (a) is the time required prior to initiation of combustion within said subterranean formation for gas to travel through said subterranean formation between said input well and said output well at a known rate of injection of said gas into said input well and at a known gas pressure at said input well and at said output well, (b) is the gas saturation in said subterranean formation prior to initiation of combustion within said subterranean formation, and (c) is the porosity of said subterranean formation, whereby the third term may be determined from the equation:

$$(1) \quad S = \frac{2.339Qt}{\phi h L^2 (P_w + P_o) \theta}$$

in which equation S is the gas saturation expressed as the fraction of the pore volume of the material of said subterranean formation occupied by gas; Q is the rate at which gas is injected into said subterranean formation through the input well expressed as standard cubic feet per hour; t is the time required for gas to travel through said subterranean formation between the input well and the output well expressed as hours; ϕ is the porosity of said subterranean formation expressed as the fraction of the bulk volume of the material of said subterranean formation occupied by pore space; h is the thickness of said subterranean formation expressed as feet; L is the distance between the input well and the output well expressed as feet; P_w is the pressure at which the gas is injected into the input well expressed as pounds per square inch; P_o is the pressure at which the gas reaches the output well expressed in pounds per square inch; and θ is a dimensionless time factor related to P_w and P_o and the well pattern and has a value taken from the accompanying figure; initiating combustion within said subterranean

formation, supplying combustion supporting gas to said subterranean formation through said input well, and measuring at a time subsequent to initiation of combustion in and following supplying of combustion supporting gas to said subterranean formation the time required for gas to travel through said subterranean formation between said input well and said output well at a known rate of injection of said gas into said input well and at a known gas pressure at said input well and at said output well, whereby the term θ may be determined from the equation:

$$(2) \quad \theta = \frac{2.339Qt}{\phi h L^2 (P_w + P_o) S}$$

in which equation each term has the definition as in Equation 1 and S has the same value as in Equation 1, and the location of the flame front within said subterranean formation may be determined from the equation:

$$(3) \quad FFL = \frac{\theta_2 S}{\theta_1}$$

in which equation FFL is the location of the flame front expressed as the fraction of the distance between the input well and the output well; θ_1 has the value of θ in Equation 1; θ_2 has the value of θ in Equation 2; and S has the value of S in Equations 1 and 2.

3. In the process for the recovery of hydrocarbon materials from a subterranean formation containing hydrocarbons and having an input well leading thereto and at least one output well leading therefrom by combustion within said subterranean formation wherein a flame front travels through said subterranean formation from said input well to said output well, the steps comprising measuring the distance between said input well and said output well, the thickness of said subterranean formation, and the porosity of said subterranean formation, measuring prior to initiation of combustion within said subterranean formation one of two terms (a) and (b), of which two terms (a) is the time required for gas to travel through said subterranean formation between said input well and said output well at a known rate of injection of said gas into said input well and at a known gas pressure at said input well and at said output well, and (b) is the gas saturation in said subterranean formation whereby the second term may be determined from the equation:

$$(1) \quad S = \frac{2.339Qt}{\phi h L^2 (P_w + P_o) \theta}$$

in which equation S is the gas saturation expressed as the fraction of the pore volume of the material of said subterranean formation occupied by gas; Q is the rate at which gas is injected into said subterranean formation through the input well expressed as standard cubic feet per hour; t is the time required for gas to travel through said subterranean formation between the input well and the output well expressed as hours; ϕ is the porosity of said subterranean formation expressed as the fraction of the bulk volume of the material of said subterranean formation occupied by pore space; h is the thickness of said subterranean formation expressed as feet; L is the distance between the input well and the output well expressed as feet; P_w is the pressure at which the gas is injected into the input well expressed as pounds per square inch; P_o is the pressure at which the gas reaches the output well expressed in pounds per square inch; and θ is a dimensionless time factor related to P_w and P_o and the well pattern and has a value taken from the accompanying figure; initiating combustion within said subterranean formation, supplying combustion supporting gas to said subterranean formation through said input well, and measuring at a time subsequent to initiation of combustion in and following supplying of combustion supporting gas to said subterranean formation the time required for gas to travel through said subterranean formation between said input well and said output well at a known rate of injection of said gas into said input

well and at a known gas pressure at said input well and at said output well, whereby the term θ may be determined from the equation:

$$5 \quad (2) \quad \theta = \frac{2.339Qt}{\phi h L^2 (P_w + P_o) S}$$

in which equation each term has the definition as in Equation 1 and S has the same value as in Equation 1, and the location of the flame front within said subterranean formation may be determined from the equation:

$$(3) \quad FFL = \frac{\theta_2 S}{\theta_1}$$

15 in which equation FFL is the location of the flame front expressed as the fraction of the distance between the input well and the output well; θ_1 has the value of θ in Equation 1; θ_2 has the value of θ in Equation 2; and S has the value of S in Equations 1 and 2.

4. In the process for the recovery of hydrocarbon materials from a subterranean formation containing hydrocarbons and having an input well leading thereto and at least one output well leading therefrom by combustion within said subterranean formation wherein a flame front travels through said subterranean formation from said input well to said output well, the steps comprising measuring the distance between said input well and said output well, the thickness of said subterranean formation, and the porosity of said subterranean formation, measuring prior to initiation of combustion within said subterranean formation the time required for gas to travel through said subterranean formation between said input well and said output well at a known rate of injection of said gas into said input well and at a known gas pressure at said input well and at said output well whereby the gas saturation in said subterranean formation may be determined from the equation:

$$(1) \quad S = \frac{2.339Qt}{\phi h L^2 (P_w + P_o) \theta}$$

40 in which equation S is the gas saturation expressed as the fraction of the pore volume of the material of said subterranean formation occupied by gas; Q is the rate at which gas is injected into said subterranean formation through the input well expressed as standard cubic feet per hour; t is the time required for gas to travel through said subterranean formation between the input well and the output well expressed as hours; ϕ is the porosity of said subterranean formation expressed as the fraction of the bulk volume of the material of said subterranean formation occupied by pore space; h is the thickness of said subterranean formation expressed as feet; L is the distance between the input well and the output well expressed as feet; P_w is the pressure at which the gas is injected into the input well expressed as pounds per square inch; P_o is the pressure at which the gas reaches the output well expressed in pounds per square inch; and θ is a dimensionless time factor related to P_w and P_o and the well pattern and has a value taken from the accompanying figure; initiating combustion within said subterranean formation, supplying combustion supporting gas to said subterranean formation through said input well, and measuring at a time subsequent to initiation of combustion in and following supplying of combustion supporting gas to said subterranean formation the time required for gas to travel through said subterranean formation between said input well and said output well at a known rate of injection of said gas into said input well and at a known gas pressure at said input well and at said output well, whereby the term θ may be determined from the equation:

$$(2) \quad \theta = \frac{2.339Qt}{\phi h L^2 (P_w + P_o) S}$$

in which equation each term has the definition as in Equation 1 and S has the same value as in Equation 1,

and the location of the flame front within said subterranean formation may be determined from the equation:

$$(3) \quad FFL = \frac{\theta_2 S}{\theta_1}$$

in which equation FFL is the location of the flame front expressed as the fraction of the distance between the input well and the output well; θ_1 has the value of θ in Equation 1; θ_2 has the value of θ in Equation 2; and S has the value of S in Equations 1 and 2.

5. In the process for the recovery of hydrocarbon materials from a subterranean formation containing hydrocarbons and having an input well leading thereto and only one output well leading therefrom by combustion within said subterranean formation wherein a flame front travels through said subterranean formation from said input well to said output well, the steps comprising measuring the distance between said input well and said output well, the thickness of said subterranean formation, and the porosity of said subterranean formation, measuring prior to initiation of combustion within said subterranean formation the time required for gas to travel through said subterranean formation between said input well and said output well at a known rate of injection of said gas into said input well and at a known gas pressure at said input well and at said output well whereby the gas saturation in said subterranean formation may be determined from the equation:

$$(1) \quad S = \frac{2.339Qt}{\phi h L^2 (P_w + P_o) \theta}$$

in which equation S is the gas saturation expressed as the fraction of the pore volume of the material of said subterranean formation occupied by gas; Q is the rate at which gas is injected into said subterranean formation through the input well expressed as standard cubic feet per hour; t is the time required for gas to travel through said subterranean formation between the input well and the output well expressed as hours; ϕ is the porosity of said subterranean formation expressed as the fraction of the bulk volume of the material of said subterranean formation occupied by pore space; h is the thickness of said subterranean formation expressed as feet; L is the distance between the input well and the output well expressed as feet; P_w is the pressure at which the gas is injected into the input well expressed as pounds per square inch; P_o is the pressure at which the gas reaches the output well expressed in pounds per square inch; and θ is a dimensionless time factor related to P_w and P_o and has a value taken from the curve A in the accompanying figure; initiating combustion within said subterranean formation, supplying combustion supporting gas to said subterranean formation through said input well, and measuring at a time subsequent to initiation of combustion in and following supplying of combustion supporting gas to said subterranean formation the time required for gas to travel through said subterranean formation between said input well and said output well at a known rate of injection of said gas into said input well and at a known gas pressure at said input well and at said output well, whereby the term θ may be determined from the equation:

$$(2) \quad \theta = \frac{2.339Qt}{\phi h L^2 (P_w + P_o) S}$$

in which equation each term has the definition as in Equation 1 and S has the same value as in Equation 1, and the location of the flame front within said subterranean formation may be determined from the equation:

$$(3) \quad FFL = \frac{\theta_2 S}{\theta_1}$$

in which equation FFL is the location of the flame front expressed as the fraction of the distance between the input well and the output well; θ_1 has the value of θ in Equation 1; θ_2 has the value of θ in Equation 2; and S has the value of S in Equations 1 and 2.

6. In the process for the recovery of hydrocarbon materials from a subterranean formation containing hydrocarbons and having an input well leading thereto and four output wells leading therefrom, said output wells being spaced 90° from each other on a circle having the input well as its center, by combustion within said subterranean formation wherein a flame front travels through said subterranean formation from said input well to one of said output wells, the steps comprising measuring the distance between said input well and said one of said output wells, the thickness of said subterranean formation, and the porosity of said subterranean formation, measuring prior to initiation of combustion within said subterranean formation the time required for gas to travel through said subterranean formation between said input well and said one of said output wells at a known rate of injection of said gas into said input well and at a known gas pressure at said input well and at said one of said output wells whereby the gas saturation in said subterranean formation may be determined from the equation:

$$(1) \quad S = \frac{2.339Qt}{\phi h L^2 (P_w + P_o) \theta}$$

in which equation S is the gas saturation expressed as the fraction of the pore volume of the material of said subterranean formation occupied by gas; Q is the rate at which gas is injected into said subterranean formation through the input well expressed as standard cubic feet per hour; t is the time required for gas to travel through said subterranean formation between the input well and said one of said output wells expressed as hours; ϕ is the porosity of said subterranean formation expressed as the fraction of the bulk volume of the material of said subterranean formation occupied by pore space; h is the thickness of said subterranean formation expressed as feet; L is the distance between the input well and said one of said output wells expressed as feet; P_w is the pressure at which the gas is injected into the input well expressed as pounds per square inch; P_o is the pressure at which the gas reaches said one of said output wells expressed in pounds per square inch; and θ is a dimensionless time factor related to P_w and P_o and has a value taken from the curve B in the accompanying figure; initiating combustion within said subterranean formation, supplying combustion supporting gas to said subterranean formation through said input well, and measuring at a time subsequent to initiation of combustion in and following supplying of combustion supporting gas to said subterranean formation the time required for gas to travel through said subterranean formation between said input well and said one of said output wells at a known rate of injection of said gas into said input well and at a known gas pressure at said input well and at said one of said output wells, whereby the term θ may be determined from the equation:

$$(2) \quad \theta = \frac{2.339Qt}{\phi h L^2 (P_w + P_o) S}$$

in which equation each term has the definition as in Equation 1 and S has the same value as in Equation 1, and the location of the flame front within said subterranean formation may be determined from the equation:

$$(3) \quad FFL = \frac{\theta_2 S}{\theta_1}$$

in which equation FFL is the location of the flame front expressed as the fraction of the distance between the input well and said one of said output wells; θ_1 has the value of θ in Equation 1; θ_2 has the value of θ in Equation 2; and S has the value of S in Equations 1 and 2.

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