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Recovering Nigerian Heavy Crude Oil in Non-Conventional Reservoirs using Thermal Recovery Methods

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ABSTRACT

Nigeria imports heavy oil, even though abundant heavy oil reserve has been reported. Most of the reserves are in the non-conventional reservoirs, such as tar sands. In this paper, the prospects of recovering heavy oil in non-conventional reservoirs using thermal recovery methods are reviewed. The objective of this study is to determine the best thermal recovery method that can be used in recovering heavy oil in Nigerian non-conventional reservoirs.

To fulfill the stated objective, the reservoir and fluid properties are estimated from published geological and geophysical data. The reservoir rock and fluid properties are then compared with those of other reservoirs where thermal recovery methods have been applied successfully.

Results from this study show that the rock and fluid properties in Nigerian non-conventional reservoirs are similar to those reservoirs elsewhere where thermal recovery methods have been successfully applied. However, the in-situ combustion thermal recovery method is recommended because the thinness of the reservoir sands will make application of steam flooding or hot water-flooding unprofitable due to excessive heat losses. It is also recommended that cold water should be injected during the in-situ combustion process to recuperate the excessive heat in the burned zone and transfer it to the unburned zone. Injection of water will also reduce the fuel concentration and hence, the air requirement. This will in turn reduce the air compression cost.

Keywords; thermal recovery, in- situ combustion, non - conventional reservoir, rock and fluid properties, tar sand, Heavy crude and gravity

INTRODUCTION

Heavy crude oils have been defined, somewhat arbitrarily, as crude oils with gravity of 10 to 200 API. The lower gravity limit is not well established and includes hydrocarbons resident in porous media in fluid or semi fluid state and, therefore, may include oils with a gravity as low as 6 to 7 °API in some cases. This total gravity range corresponds to a range of specific gravity from 0.934 to 1.029. Nigerian crude oil in the non-conventional reservoir has specific gravity within the stated range and therefore may be classified as heavy oils.

Nigerian heavy crude oil reserve is estimated to be about 35 to 45 billion barrels. About 4.3 billion barrels of the reported reserves are considered to be in the main producing fields of the Niger Delta, while the rest are in non-conventional reservoirs such as tar sands and oil shales. The API gravity of the heavy oil found in the Niger Delta is about 8.3 to 20° API, while those non-conventional reservoirs are about 5.3 to 16.4° API. The heavy oil is found in two pay zones, Sand X and Sand Y shown in Figure 1. Estimated reservoir properties from geological and geophysical work done in the field are shown in Table 1. Table 1 also contains oil saturation and porosity values calculated in this study.

Thermal recovery methods are used for recovering heavy oil crude. The main objective of these methods is to reduce the high viscosity of the oil and hence increase the oil mobility by heating the reservoir. Heat energy can be generated directly in the reservoir as in the in-situ combustion process, or it can be

generated externally and transferred to the reservoir by a carrier fluid such as steam in the steam drive process. During in-situ combustion process, a combustion front is created and propagated through the reservoir. The rock is heated directly at the combustion front and indirectly by the movement of hot combustion gases, unburned air, volatile hydrocarbons, and steam through the reservoir. Figure 2 is a schematic diagram of saturation and temperature distribution during an in-situ combustion process. The zones that can be distinguished in Figure 2 include; the burned zone, combustion zone, evaporation zone condensation zone (steam plateau), water bank zone, oil bank zone, and virgin formation zone. The oil back zone contains the displaced oil while the steam plateau zone contains the undisplaced oil which is usually converted to fuel. Part of the oil is used as fuel during in-situ combustion process while a substantial amount of oil is recovered. The amount of oil used as fuel (fuel concentration) depends on factors which include the API gravity of the oil. The fuel concentration increases as API gravity of the oil decreases. For heavy oil, the fuel concentration may be excessive. This results to excessive combustion temperatures and high air requirement.
Figure 3 is the schematic diagram of the steam injection process. The reservoir temperature during steam injection process depends on factors which include the steam quality and the reservoir conditions. Higher reservoir temperatures are attained during in-situ combustion process than during steam injection process. In this study, the prospect of recovering Nigerian non-conventional heavy oil using thermal methods is examined. Nigerian heavy non-conventional oil reservoir and fluid properties estimated in this study from published data are compared with data from reservoirs where thermal recovery processes have been successfully applied. The best thermal recovery method is chosen and associated problems and remedies discussed.

Calculation of Reservoir Parameters

Evaluation of reservoirs for thermal recovery requires knowledge of reservoir parameters. Such parameters include oil saturation, porosity, formation thickness, permeability, etc. Here, the oil saturation and porosity for the non-conventional reservoirs are calculated from geological and geophysical data in Table 1.

Calculation of Porosity

Porosity is measure of pore spaces within a rock and may be derived from the bulk density Pb of clean, liquid filled formations, when the matrix density ρma and the density of the liquid pi' are known, using the relation:

$$\phi = \frac{\rho ma - \rho b}{\rho ma - \rho t} \qquad (1)$$

The assumption in Equation 1, which acceptable for common formation materials, is that electron density is proportional to actual density. The fluid density Pf in Equation 1 is defined as:

$$\rho f = \rho_g S_g + \rho_o S_o + \rho_w S_w \quad (2)$$

The gas saturation S_g, in Nigerian non-conventional heavy oil reservoirs is small and may be assumed to be zero. The API gravity of Nigerian heavy oil in non-conventional reservoirs is the range of 5.3 - 14.6° API. This corresponds to oil density of 0.9685 - 1.034 gm/cc. Since the density of formation water is about 1 gm/cc, the fluid density in Equation 1 may be taken as 1 gm/cc. Using the bulk density value given in Table 1 and matrix density of 2.65 gm/cc, the porosity is calculated using Equation 1 to be:

ϕ = (2.65 - 2.24)/(2.65 - 1.0) = 0.25

Calculation of Fluid Saturation

The water saturation of a clean formation can be expressed in terms of its true resistivity as:

$$S_w^n = FR_w/R_t \qquad (3)$$

The saturation exponent n, is generally assumed to be 2. The formation factor F, may be determined using the equation:

$F = a/\phi^m$ (4)

Where:
a = Constant
m= Cementation factor
ϕ = porosity

The values of 'm' and 'a' used by different authors and the calculated values of formation factor, F for non-conventional reservoirs are shown in Table 2. An "F" value of 12.75 is used in Equation 3 for calculating saturation. This is the average value calculated using Archie's equation for the sand and Winsauer et al equation.

The resistivity of formation water R_w, is estimated to be ohm-m. Substitute the values of formation factor, formation water resistivity, and measured resistivity (see Table 1) of the oil bearing formation into Equation 2, the water saturation is calculated. The corresponding hydrocarbon saturation S_h, is calculated using the saturation constraint equation:

$S_h = 1 - S_w$ (5)

As gas saturation is assumed to be zero, the hydrocarbon saturation, S_h will be equal to the oil saturation, S_o. Table 1 shows the measured resistivity values and the corresponding oil saturation calculated in this study. The calculated oil saturation is high (0.81 – 0.92). This is also true to many known heavy oil reservoirs. From the calculated results, the product of porosity and average initial saturation is 0.2. This is close to the value of .18 assumed by Adegoke.

Evaluation of Nigerian Non-Conventional Reservoirs

Different criteria have been used for selection of reservoirs amenable to thermal recovery. Any such set of criteria are affected by the current and local economic climate. These criteria are determined by technical considerations that affect the following:

1. The ability to generate heat within or inject heat into the reservoir
2. The ability to displace oil
3. The ability to recover the oil in a controlled manner.

It is difficult to translate these considerations into specific values of properties to serve as criteria for determining the applicability of thermal recovery processes. But experience has shown that the application of thermal recovery methods to reservoirs with rock and fluid properties as shown in Table 3 have yielded favorable results. Details of how the properties influence thermal recovery processes are discussed in the literature. Chu and Poettmann also published some screening guides. Although the limits set in the screening guides are slightly different, their application usually yields essentially the same results.

The values of rock and fluid properties in Table 3 will for now serve as guidelines for evaluating Nigerian non- conventional heavy oil reservoirs. However, it is usually better that each reservoir be examined individually as though there are no guidelines, especially where the reserves are great enough, as in Nigeria's case, to support engineering studies. Discussion on criteria for application of thermal recovery methods in relation to some known reservoir conditions, rock and fluid properties of Nigerian heavy oil reservoirs follows.

Reservoir Conditions

The reservoir conditions considered are reservoir pressure, temperature and depth. Both reservoir pressure and temperature increase with depth. This implies that application of thermal recovery methods in deep reservoirs will require big generators (for steam or hot water flooding) and compressors (for in-situ combustion) because of the high injection pressure. For steam and hot water flooding, a substantial amount of heat may be lost in the wellbore if the reservoir is deep. In addition, for steam, the latent heat of vaporization decreases as pressure increases. Hence, the heat finally released to the reservoir many not be substantial if the reservoir is deep. Finally, the temperature in deep reservoir is usually high and the additional increase in temperature during steam or hot water flooding may not be appreciable to affect the viscosity of the oil substantially.

On the other hand, when reservoirs are shallow and reservoir pressure low, injected fluids may flow to out-crops resulting to loss of control. The loss of control is undesirable, especially for in-situ combustion process. Based on the given facts and experience, the criteria given in able are recommended. The Nigerian non- conventional reservoirs, Sand X and Sand Y, are shallow and the reservoir pressures are low. Sand X is so shallow (see Table 1) that application of thermal recovery methods in this sand is not recommended because of the possibility of loss of control. Sand Y is also shallow but because it is overlain by a shale bed it is unlikely that there will be loss of control as shale is impervious. If thermal recovery process is initiated in Sand Y, part of the generated or transferred heat will be lost by conduction to Sand X. Hence, some of the oil in Sand X can be recovered. Since higher temperatures are attained in the reservoir during in-situ combustion than during steam or hot water flooding, more heat will be lost to Sand X if in-situ combustion is applied. This implies that more oil will be recovered from Sand X if in-situ combustion rather than steam or hot water flooding is applied in Sand Y.

Reservoir Rock and Fluid Properties

Properties considered under reservoir rock and oil include; reservoir rock type, thickness, porosity, permeability, oil saturation, oil gravity, viscosity and type. These properties will be considered under different headings.

Reservoir Thickness

During thermal recovery process, heat is generated or injected into the reservoir. Recovery efficiency of thermal recovery methods depends on several factors which include the amount of heat which remains in the reservoir. The heat in the reservoir is lost primarily by conduction to overburden and under burden formations. The heat loss is inversely proportional to square of the sand thickness. Hence, thin reservoirs loss more heat than thick reservoirs during thermal recovery processes.

Heat loss greatly affects steam and hot water flooding processes and thus limits their application to only thick reservoirs. In Nigerian non-conventional reservoirs, Sand Y has a thickness of about 3-26 meters. This is considered thin for application of steam and hot water flooding process. The in-situ combustion method is thus recommended.

Porosity

During thermal recovery, a substantial amount of heat is used in heating the sand grains. As porosity increases, the sand grain volume decreases. Less sand and more oil will be heated. In addition, as porosity increase, the amount of recoverable oil also increases. The Nigerian non-conventional reservoir has adequate porosity (25%) for application of thermal recovery processes.

Reservoir Rock Type and Permeability

Thermal recovery methods have been applied successfully in sand and sandstone reservoirs with good permeability, heterogeneities may be undesirable because of channeling of injected fluid. Also, reservoirs with low pressure and moderate or poor permeability have proved unsusceptible to steam flooding, the sands shown in Figure 1 that make up part of the non-conventional reservoirs comprise fine to medium-grained sands inter bedded with thin layers of gray sandy clay and dark gray shales. Hence, the reservoirs (Sand X and Sand Y) may not have good permeability; the reservoir pressures are also low. Hence, steam flooding may not be applicable. Based on the reservoir rock type and permeability, in-situ combustion method is recommended because it is not handicapped by the absence of reservoir pressure or restricted permeability.

Oil Saturation

After steam or hot water flooding process, some oil is still left undisplaced. During in-situ combustion process, part of the oil is burned as fuel. In all thermal recovery processes, some of the displaced oil cannot be recovered. Hence, before thermal recovery is initiated, a substantial amount of oil must be in place to support the thermal recovery operation. The economics must also be right to justify the huge investment. The oil saturation in Nigerian non-conventional reservoir is about 0.81 to 0.92. This saturation is high enough to warrant considering applying thermal recovery methods.

Oil Specific Gravity and Viscosity

There is generally no unique relationship between oil specific gravity and viscosity; but, in general, viscosity increases as oil specific gravity increases. Very high specific gravity oil is essentially immobile and this makes it difficult to initiate a moving oil front. On the other hand, low specific gravity oil has high mobility and a combustion front cannot be sustained because of insufficient fuel. Most of the oil will be displaced before the arrival of the combustion front.

In forward in-situ combustion process, the production of combustion, oil and water flow into relatively cool region. This flow is impeded if the mobility of the fluid in the cool region in very low. Hence, the upper limit of the oil gravity for which forward in-situ combustion is applicable is about 0.92. For reverse in-situ combustion, there is no such upper limit because unlike in forward in-situ combustion, oil, water and products of combustion flow in regions of the reservoir that has been heated. This is because in reverse in-situ combustion, the combustion front moves in the direction opposite to the flow of fluids. However, more oil is used as fuel during reverse in-situ combustion.

Steam and hot water flooding are more suited for recovery of high specific gravity oil, this is because such oil respond more effectively to an increase in temperature. That is, the viscosity reduction for such crudes is substantial with slight increase in temperature. It is known that hot water and steam flooding are uneconomical for recovering intermediate gravity oil. The heavy oil in Nigeria tar sand reservoir has a gravity of about 0.969 to 1.034. This implies that based on the gravity of the crude, both steam injection and in-situ combustion methods can be applied.

Reservoir Oil Type

During in-situ combustion, part of the oil is converted to coke which is used as fuel. The conversion of oil to coke depends on several factors which include the oil type. The conversion is enhanced if the oil contains heavy compounds such as asphalt and naptha. Analysis performed on heavy oil from Nigerian non-conventional reservoir show that the oil contains heavy ends and will be susceptible to application of in-situ combustion thermal recovery method. For steam or hot water flooding, the oil type is not a critical factor.

From the above discussion and information shown in shown in Tables 1 and 3, it may be inferred that Nigeria heavy oil reservoirs satisfy most of the criteria for application of some thermal recovery methods. However, the in-situ combustion process will he preferred because of the thickness of the sand and other stated factors. Also, in-situ combustion has proved useful in reservoirs where steam has worked and more importantly where steam has failed. It is necessary to point out that the criteria shown in Table 3 are not comprehensive because some factors like sand continuity, outcrop and formation dip which also affect thermal recovery processes are not included. Discussion on method of estimating the fuel concentration in Nigerian non-conventional reservoirs follows.

Estimation of Fuel Concentration

Fuel concentration is a very important parameter in in-situ combustion process. It is used for calculation of expected oil recovery and air requirement. The air requirement determines the size of air compressor needed for in-situ combustion operations. Also, to sustain a combustion front in in-situ combustion process, enough fuel must be available. However, if excessive fuel is available, large air compression cost will be incurred.

Experiments by Showalter and Alexander et al show that fuel concentration increase as API gravity of the oil decreases. However, no unique relationship between fuel concentration and API gravity has been established from the experiments. In this section, a simulation study by the author to investigate the relationship between fuel concentration and API gravity is discussed.

The finite-difference thermal simulator used for this study has the following three phases: oil, gas and water. The absence of a solid phase implies that undisplaced oil is not converted to coke before being burned as fuel. Combustion of the undisplaced oil is considered to be instantaneous, and is limited only by the oxygen supply. This simplified model, eliminates the need for reaction- rate equations. The combustion reaction is the source of energy, and it creates and destroys components according to reaction stoichiometry given by Benham and Poettmann1 as:

$CH^{n} + [2^{m+1} + m]0^{2} \rightarrow [m]co^{2} + [1]CO + nH^{2\circ}$ (6)

[2m+2 4 [m+1 [1+m 2

$2m + 1 + m\ 0_2 - m\ CO_2 + 1\ CO + nH_20$ (6)

$CHn + 2_{m + 2 + 4} \quad {}_{m + 1} \quad {}_{1 + m \quad 2}$

In Eq. 1, m is the ratio moles of carbon dioxide, CO_2, to carbon monoxide, CO, produced. It is found by analyzing combustion gases. CH_2 is the unit molecular weight of the fuel and n is the carbon-hydrogen ratio. A summary of the features of the simulator is shown in Table 4. Further discussion of the simulator may be found in Reference 16.

A laboratory combustion run was simulated so as to validate the model. The properties of the laboratory sandpack are shown in Table 5. The laboratory tube-run and analysis of the result have been given by Pande. Results obtained from the analysis of the tube-run were used as input parameters for the simulation run. Additional parameters used for the simulation run are shown in Table 6. Some results from the laboratory and simulation runs are shown in Figs. 4 and 5. Figure 4 shows the temperature profiles at two different times. The profiles for the simulated and laboratory runs match reasonably well suggesting that the model is adequate. The difference between the temperature profiles at the injection point may be caused by pre-ignition heating used in the laboratory run. The effect of pre-ignition heating was not considered in the thermal model. Figure 5 shows the cumulative oil production for both the simulated and laboratory runs. The match between the results is also good. Hence, the simulator is considered useful for the study.

Further simulation runs were made to investigate the effect of API gravity on fuel concentration. The viscosity-temperature-API gravity values used for the simulation were taken from the correlation published by Beal. Figure 6 shows the relationship between viscosity, temperature and API gravity. Figure 6 shows that within the temperature range expected during in-situ combustion, there is a unique relationship between API gravity and oil viscosity. Results from simulation runs on the effect of oil API gravity are shown in Figure 7. The fuel concentration appears to decrease linearly with increase in API gravity. Hence, the air requirement will vary in a similar manner with API gravity as fuel concentration is directly proportional to air requirement if the combustion efficiency is constant. The high fuel concentration for low API gravity oil is primarily due to the low mobility of such oil. The combustion front velocity shows an inverse trend. This is because the less fuel there is to be burned, the faster the front velocity. For API gravity greater than 20, simulated results shown in Fig. 7 agree with experimental results published b Showwalter. The results published by Alexander1 show more scatter. For API gravity greater than 20, both simulated and experimental results show that fuel concentration vanes linearly with

API gravity. For API gravity less than 20, the simulated and experimental results do not agree. It should also be noted that experimental results of Showalter13 and Alexander14 et al do not agree. The disagreements on the effect of API gravity on fuel concentration is probably because API gravity is not a unique correlating function with oil viscosity which plays an important role in determining the amount of undisplaced oil that is converted to fuel. This disagreement is more manifest in the results obtained for the low API gravity oil. For simulation discussed in this paper, a unique relationship between API gravity and viscosity is assumed (see Fig. 6). This explains why simulated results show that fuel concentration varies linearly with API gravity, even at low API gravity.

Results shown in Fig. 7 are useful for cases where the viscosity-temperature relationship follow the trend shown in Figure 6. In cases where the trend is not followed, a pseudo API gravity of the oil can be defined based on the viscosity-temperature relationship shown in Figure 6. With the pseudo API gravity, Figure 7 can still be used to estimate the fuel concentration. For cases where the viscosity temperature relationship of the oil does not follow any of the trends shown in Figure 6, the fuel concentration should not be estimated using Figure 7.

For the Nigerian nonconventional reservoir, assuming an API gravity of 10, the fuel concentration estimated from Figure 7 is about 2.3 lb/c ft. The expected temperatures, obtained from simulation, for a 10° API gravity is shown in Figure 8. Similar results will be obtained if in-situ combustion process is applied to the nonconventional reservoirs in Nigeria. In Figure 8, the temperatures in the burned region (behind the combustion front) are high. This situation is undesirable because the generated heat is in the region where it is not required. This situation is undesirable because the generated heat is in the region where it is not required. This situation can be remedied by injecting water to recuperate the heat and transfer it to regions ahead of the combustion front. There are differences in the reported reduction in air requirement achieved by injection of water. From the data published by Dietz and Weijdema the air requirement can be reduced by about 60% if the injected water-air ratio of 1 barrelIMSCF is used.

CONCLUSIONS AND RECOMMENDATIONS

From available information, there is a possibility of recovering Nigerian heavy oil using thermal recovery methods. The in-situ combustion process is preferred because of the thickness of the sands and other factors. The problem of application of in-situ combustion process for recovery of low API gravity oil is the excessive fuel concentration which in turn results to high air requirement. The air requirement greatly affects the economics of in-situ combustion projects. However, with the injection of water the fuel concentration can be reduced. The air requirement is in turn reduced making the application of in-situ combustion process feasible.

In addition to this work, some laboratory and more simulation studies should be done before any fund is committed to the field project. Simulation studies are required to complement laboratory studies and also to investigate the effects of some parameters which may be difficult to study in the laboratory. Onyekonwu et al have shown that the process variables that influence the in-situ combustion process can be investigated using thermal simulators.

Nomenclature

a = constant in Archie's equation
d = density, gin/cc
F formation factor
m = cementation factor
n saturation exponent
R = resistivity, ohm-rn
Rt = resistivity of formation, ohm-rn
S saturation, fraction of pore volume

0= porosity, fraction of bulk volume
Pb = density of clean liquid-filled formation, gin/cc
P = fluid density, gin/cc
P_{ma} = matrix density, gin/cc
Subscripts
f = fluid
g = gas
o = oil
w = wa

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Table 1: Reservoir data for Nigerian tar sand reservoir

Parameter	Sand X	Sand Y
Thickness, m	10-20	3-26
Depth, m	355	
Bulk density, gm/cc	2.24	2.24
API gravity	5.3-1 4.6	5.3-1 4.6
Caloric value, KJ/Kg	43000	43000
Carbon/Hydrogen ratio	0.68	616
Average molecular weight	616	300-500
Resistivity, ohm-rn	100-300	0.25
Porosity*	0.25	0.89-0.92
Oil Saturation*	0.81-0.89	Sand Y

* Values calculated in this study

Table 2: Values of formation factor, F

Reference No	Cementation Factor, m	Constant, a	$F = a/0^m$
4	2	0.81	13.12
4	2	1.0	16.2
5	2.15	0.62	12.37

Table 3: Criteria for application of thermal recovery methods

Parameters	In-Situ combustion	Steam or Hot Water Flooding
Reservoir Conditions Depth, m Reservoir Pressure, bars Temperature, C	>100 TL NC	<1000 <100 NC
Reservoir Rock Type Thickness, m Porosity, fraction Permeability, urn Oil saturation, fraction	sand, sandstones 3-25 or more >0.18 >o.oi >0.3	sand, sandstone with low clay content 10-100 >0.18 >0.1 >0.3

Reservoir Oil Specific gravity Viscosity at reservoir conditions, Pascal-s Oil type	0.82-0.98 0.02 with asp1ialt and naphta compounds	>0.98 0.05-2 NC
Favourables	Low vertical permeability, consolidated sands	high net to gross pay sand, shallow sands, economical fuel available

TL = Technical limit
NC = Not a critical factor

Table 4: Summary of features of the thermal simulator
Three phases: oil, water and gas. Five components: H 0, deadil, oxygen, CO ,and CO-N. 2 2 The combustion reaction is the source of energy; it creates and destroys components according to stoichiometry. Any undiisplaced oil is burned as fuel. One-dimensional fluid flow and heat transfer within the reservoir. Relative permeability's are functions of saturation only. Gravity and capillary effects are not considered. Fluid PVT properties are functions of pressure, temperature, and composition. Automatic time-steps are based on changes in the dependent variable. A fine moving grid is used for better representation of temperatures ahead of the burning front. Variable switching is used for improved accuracy.

Table 5: Sandpack properties	
Total length of the tube, cm	99.5
Length of the sandpack, cm	90.5
Radius of the tube, cm	3.7465
Radius of the thermowell, cm	0.08255
Bulk volume, cc	3966.7
Sand density, gm/cc	2.67
Clay density, gm/c	2.67
Oil density, gm/cc	0.96098
Water density, gm/cc	0.99714
Weight of sand in the tube, gm	6450.6
Weight of clay in the tube, gm	323.6
Weight of oil in the tube, gm	594.8
Weight of water in the tube, gm	431.4
Pore volume, cc	1429.6
oil saturation, fraction	0.43293
Water saturation fraction	0.30261
Gas saturation, fraction	0.26446
Oil viscosity data	
Temperature, F, (C^o)	Viscosity, cp (pa-s)
80.2 (26.8)	1600 (1.600)
104.3 (40.3)	657 (0.657)
138. (59.2)	258.5 (0.2585)
175.1 (79.5)	106 (0.106)

Table 6 Additional reservoir and fluid properties					
Absolute permeability, md		6000			
Rock thermal conductivity, Btu/(hr-ft- F) (KJ/hr-m-F) 2 (12.471) 0 o -1 -1		4.9x10 (8.82x10			
Water thermal expansion coefficient, F (C o o -1 lxlO (1.8x10					
Oil thermal expansion coefficient, F (C)					
Oil compressibility, psi (Mpa)1 1		15x10 (1.03x10			
Water compressibility, psi (Mpa) -1		3x10 (2.07x10			
Rock compressibility, psi (Mpa) -1		2x10 (1.38x10			
0 0					
Gas heat capacity, Btii1bm- F (KJ/Kg- C)		0.2 (0.838)			
0 0					
Oil heat capacity,Btu/lbm- F (KJ/Kg- C)		0.5 (2.095)			
0 0					
Rock heat capacity,Btu/lbm- F (KJ/Kg- C)		0.28 (1.1732)			
Molecular weight of oil, lb/lb-mole (Kg/Kg-mole)		300			
Relative permeability data for water/oil			Relative permeability data for gas/liquid		
S_W	K_{rk}	K_{row}	S_L	K_{rg}	K_{rog}
0.00	0.000	1.000	0.13	1.0	0.0
0.2	0.014	0.17	0.191	0.999	0.005
0.395	0.029	0.112	0.25	0.769	0.01
0.433	0.046	0.102	0.294	0.724	0.017
0.515	0.088	0.086	0.357	0.621	0.028
0.569	0.117	0.076	0.414	0.504	0.042
0.614	0.143	0.065	0.49	0.371	0.067
0.663	0.176	0.05	0.557	0.303	0.097
0.719	0.217	0.037	0.63	0.156	0.115
0.75	0.226	0.029	0.673	0.096	0.126
o.805	0.292	0.02	0.719	0.058	0.138
0.85	0.337	0.012	0.789	0.000	0.164
0.899	0.517	0.003	1.0	0.000	1.000
1.0	1.0	0.0			