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Determine Factors Affecting Fuel Availability and Composition by Cell Oxidation during Laboratory Test for In-Situ Combustion

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Abstract

We determine the fuel availability and the corresponding air requirements for in–situ combustion of crude oils by using a cell oxidation technique on core samples. Since the technique is relatively quick, easy, practical and convenient for processing and evaluating reservoirs in Wadi Rajil–Hamzeh field in Azraq basin, we used the thermal recovery method. It is also a research tool which facilitates systematic study of the parameters affecting fuel availability and air requirements. The experimental results showed that the fuel availability for in–situ combustion varies with crude oil properties, oil saturation, reservoir type, porous–permeable medium, air flux, and time temperature relationship. In order to determine the actual fuel availability, these experiments should be applied in a pilot plant, and a field application is necessary to insure these results.

Keywords: cell oxidation, factors affecting fuel, thermal recovery, fuel availability and oxidation

1. INTRODUCTION

In-situ combustion is a thermal process for recovering heavy crude oil from reservoirs. The thermal energy released during the combustion of a small amount of the oil in place aims for the displacement of the remaining oil. Numerous papers have been published describing the in–situ underground combustion process [1, 2, 3, 4, 5, 6].

The laboratory work identifies the quantity and quality of fuel. However, rather than directly measuring the amount of fuel deposited, most investigators estimated the quantity of fuel deposited through stoichiometric equations developed by Nelson and McNeil [5]. Original and residual oil saturation, API gravity, Viscosity, atomic H/C ratio and Conradson Carbon residue (ASTM) were found to be the most important factors affecting fuel availability [6].

Fuel availability showed a roughly direct linear dependence on the Conradson Carbon residue and an inverse dependence on API gravity. Similar results were obtained by Showalter [7]. However, both the laboratory and field data showed that rock lithology could be more significant than oil gravity in determining how much fuel is deposited [8, 9]. Some investigations [6] indicated that high oil saturation yield greater fuel deposition. Others [10] have concluded that fuel deposition is independent of initial oil saturation, but depends on the residual oil saturation at the steam plateau. In that region, steam distillation was found to be the main mechanism for fuel deposition. Also the amount of oil saturation was found to be nearly constant in that region [11]. Similar study carried out in USSR on Oil density and air flux in which it was found to be important factor in fuel deposition [12].

In order to design the in–situ combustion project, a number of important factors must be determined in the laboratory. These factors are the amount of fuel consumed per unit of reservoir volume swept by the combustion zone; the amount of air flux required to consume this fuel; the composition of the fuel consumed; the portion of the reservoir swept by the combustion zone; the appropriate air injection rates and pressures; the amount of oil that will be recovered; the rate of oil production and the operating costs [5].

Nelson and McNiel [5] described a procedure which utilizes laboratory combustion–tube data as a basis for the calculation of some of these design factors.

The most important factors in the In-situ combustion process are the fuel formation, the combustion and the air required. In recent years air injection has received much interest of research projects in heavy crude oil reservoirs (Adetunji et al, 2005; Clara et al, 2000; Fassihi and Gillham).

Many researchers have attempted to describe the in–situ combustion process mathematically and considerable progress has been made [13,14,15]. All of the published results involve the assumptions that the fuel concentration may be made as a result of a correlation between front velocity and air flux at the burning front.

Fuel is inversely proportional to the velocity of the front to give rate of oxygen consumption [16,17]. Also the fuel reacts instantaneously with injected oxygen which gives an amount of heat that depends on the volume of the combusted fuel [6, 7, 2, 18].

This work presents laboratory data which were obtained by means of an "oxidation cell" method to determine fuel availability, composition and the corresponding theoretical air requirements. These factors are the most important for the process and necessary design consideration for in-situ combustion of asphalt and heavy crude oils under variable conditions. Samples of asphalt and heavy crude oils were taken from Wadi Rajil-Hamzeh oil filed in Jordan.

2. APPARATUS AND MATERIALS

The oxidation cell apparatus consists of a consolidated core or consolidated samples packed linearly and centrally inside a vessel which provides the necessary temperature, pressure and flow controls as shown in Fig. (1). Temperature and gas analysis equipments provide continuous records of these parameters. The consolidated cores used were 4 inches in diameter and 8-10 inches long. Different plugs were taken from several wells a 3/4 inch diameter and 2.5 inches long.

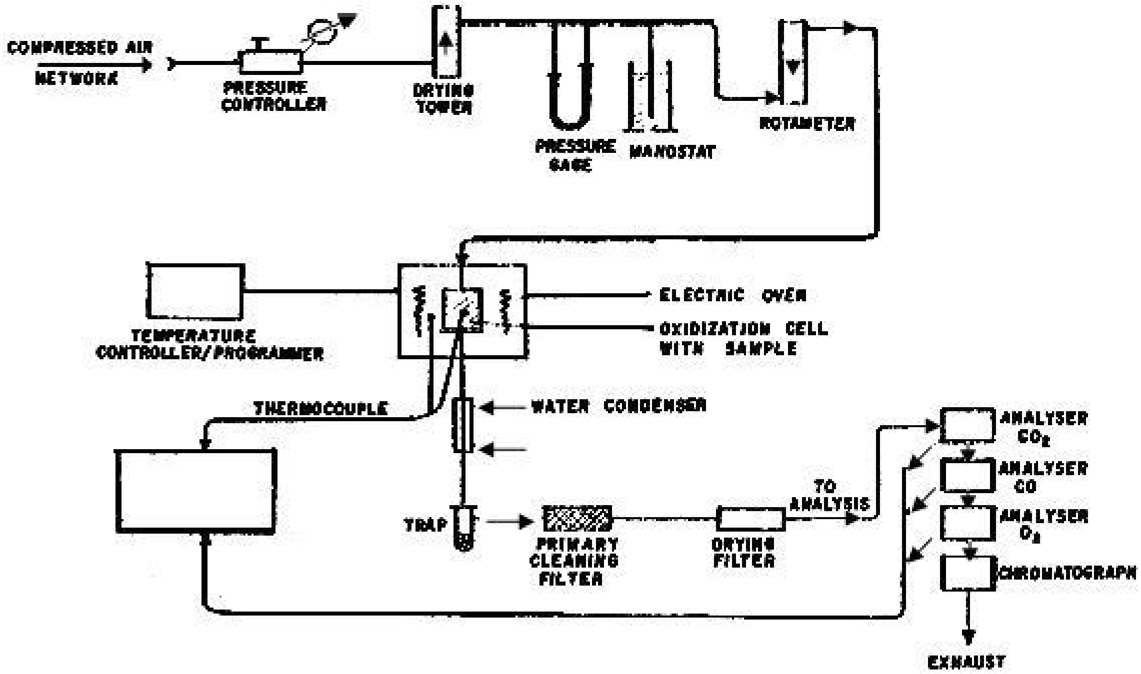

Fig. 1: Oxidation unit with programmed temperature operation.

2.1. POROUS MEDIA

Core material were taken from the Ghareb formations and crushed as porous media. The crushed material was prepared by crushing and milling until the entire samples passed through a mesh screen. The properties for these core materials are shown in table (1).

Table-1: Properties of porous Media

Core No. At depth (m)	Porosity %	Permeability (md)	Original oil saturation %
796.20	8.73	77.60	58.20
795.52	17.10	6.66	36.40
960.50	17.20	26.30	59.50
935.40	25.30	29.40	17.70
978.30	14.80	0.39	57.10
1080.75	6.84	0.94	52.6
1078.40	25.90	1377	54.80
1081.50	25.70	228	62.50
1546.4	26.70	525	49.50
1556.76	10.10	14.40	60.60

2.2. ASPHALTIC AND HEAVY OILS

The properties of asphalt and heavy crude oil were determined by lab experiments. These properties include, Gravity ^{0}API, Sulfur, Ni, V and Chromatography fractions as illustrated in table 2.

Table-2: Shows the crude oils and asphaltic Properties.

Oil and asphalt	Gravity ^{0}API	Viscosity CST at 40^{0}C	Sulphur %	Ni ppm	V ppm	Chromatography fraction %				
						Saturates	Aromatic	Polar	Non evaluated	Melting point of asphalt ^{0}C
Solid asphalt WR-2 975m	9	10000	8.80	70	160	3.5	26.6	13.7	56.2	75
Solid asphalt Hz-1 1059m	9.9	10000	5.85	70	110	2.5	27.3	14.9	55.3	80
Solid asphalt Hz-2 1079.4 m	9.9	10000	22	60	200	6.9	23.1	24.1	36.5	75

Solid asphalt Hz-2 1082m	10	6379	10.1	120	150	5.4	20.2	27.5	46.9	85
DST-1 Hz-1 1533-1555m	11.9	2000	4.38	9	130	20.3	26.8	12.1	40.8	-
DST-2 Hz-2 1955-1975m	17	426	5.23	12	125	21.5	27.5	13.5	37.5	-
2991-2997m no.9 oil	29.7	12	0.67	80	330	54.3	22.3	16.5	6.9	-
2991-2997m no.4 oil	30.9	9.6	0.45	85	280	53.2	21.1	20.1	5.6	-
Oil DST-4 3098m	34.2	5.2 at 60 ^{0}C	0.58	4	1	60.6	19.3	9.3	10.8	-

3. OXIDATION PROCEDURE

The Oxidation cell was introduced in a metal vessel. The vessel was laid in an electric resistance oven within a thermocouple which was connected to a programmed temperature recorder. The program was set to linearly survey the temperatures up to 500 ^{0}C. The analyzed samples have been prepared and introduced in the oxidation cell. The investigation was conducted on raw cores and also benzene washed (Soxhlett) at 80 ^{0}C, for five hours period each run, in which the core volume is 32 cm^3, air flux ranging from 23.4 $cm^3/m^2/hr$ to 46.8 $cm^3/m^2/hr$, and heating rate ranging from 20^{0}C to 500 ^{0}C was 80 ^{0}C /hr.

Figure (2) shows the temperature and gas–analysis data for several runs with an air flux of 23.41 $cm^3/m^2/hr$. The gas-analysis data showed how the produced gas compositions change due to run progress. During water distillation plateau, little of CO, CO_2 produced, but some oxygen reacts since the produced gas usually contains slightly less than 21% of oxygen.

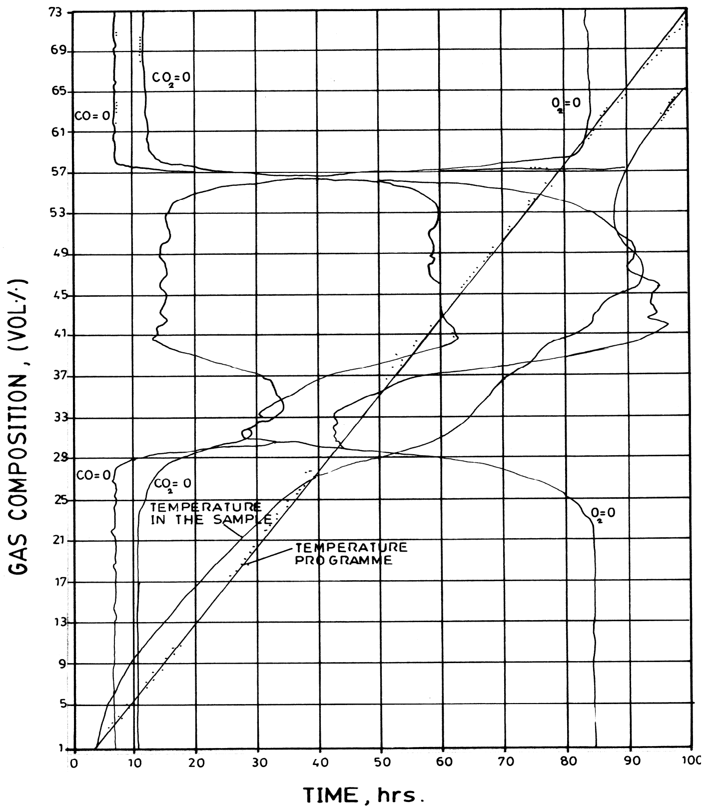

Fig. 2: temperature and gas –analysis of oxidation cell.

The diagram in figure (3) shows the variation of temperature and composition of gas analysis data for these runs with an air flow of 23.4 $cm^3/m^2/hr$. Figure (3) shows the oxidation of the crude oils in the Ghareb formation. It can be seen that the oxidation process continued up to 500°C which indicates the presence of organic materials in the samples. As the temperature is gradually increased, and the concentration of oxygen level increased, a partially oxidization of hydrocarbon material occurred, Carbon oxides (CO_2 and CO) are formed, and little of free oxygen (O_2) is exhausted.

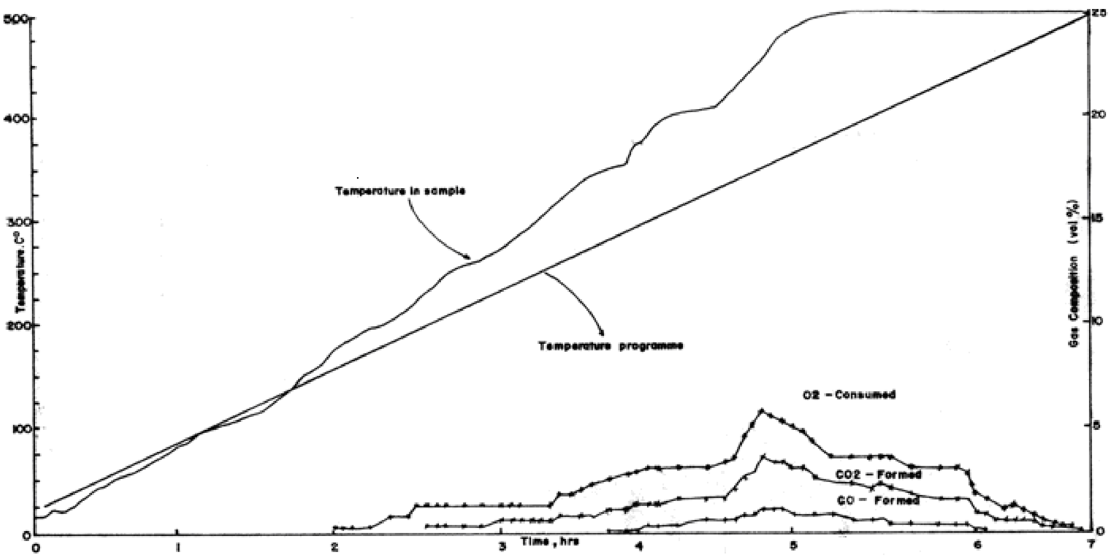

Fig 3. influence of the precence of associated organic materia on the oxidation of heavy oil and asphalt in porous media at WADI RAGIL - HAMZA area

Fig. 3: the variation of temperature and composition of gas analysis**.**

4. RESULTS AND DISCUSSION:

1. The changes in the temperature of heating the samples were nonlinear due to the good interaction between the mixtures of hydrocarbons in the rocks as shown in figure (3).

2. The rate of heating temperature were ranged between 68.9^{0}C/hr and 78 ^{0}C/hr on core samples. The heat conduction causes the difference of the rates of the heating temperature between core and device. This gives evidence that the potential flow of heavy oils under this condition is possible.

Table 3: Working Parameters.

1- air flow L/hr	20
2- air flux cm^3 /m^2/hr	23.41
3- differential pressure of gas between (input & output)(mm Col Hg)	30
4-cell volume cm^3	32.29

Table 4: Results of oxidation test.

1- initial temperature of sample ^{0}C	22.500
2- final temperature of sample ^{0}C	500.000
3- heating rate C^0/hr	68.9-78 C^0/hr
4- total quantity of O_2 consumed L	0.3946
5- total quantity of CO_2 formed L	0.1563
6- total quantity of CO formed L	0.5301
7- initial temperature at begging consumed of O_2	190.5000C^0
8- temperature at begging forms of Co_2 ^{0}C	225.5000
9- temperature at begging forms of Co ^{0}C	65 C^0
10- Total Carbon burned (Oxidation time) (gr)	0.6409
11- Carbon burned /100 gr of frame work rock total	1,7617
12- Carbon burned /100 gr of frame work rock phase I	
13- Carbon burned /100 gr of frame work rock phase II	
14- Atomic hydrogen/Carbon ratio (H/C)	4,5978
15- O_2 Consumed for forming CO L	1,7755
16- O_2 Consumed for forming additional producer & H2O [U	1,3131
17- O_2 of H2O & additional / total O_2 %	52,7642
18- CO_2/ CO ratio	5,5318
19- Consumed of O^2 m^3 / m^3 rock	77,9696
20- Air Consumed /m^3 rock (m^3 air/m^3 rock)	366,6983
21- O_2 Consumed until 200 ^{0}C (L)	0.4030
22- CO_2 formed until 200 ^{0}C (L)	0.5010
23- CO formed until 200 ^{0}C (L)	0.2000

24- Carbon burned until 200 [^{0}C] (gr)	0.5005
25- Carbon burned/100 gr rock until 200 C^0	0.5009
26- Atomic hydrogen/carbon ratio H/C until 200 ^{0}C	2.500
27- O_2 Consumed for forming CO_2 & CO until 200 ^{0}C (L)	0.5010
28- O_2 Consumed for addition producers until 200 ^{0}C (L)	0.4019
29- O_2 Addition until 200 ^{0}C L/Or total O_2 until 200 ^{0}C (%)	99,7414
30- CO_2 /CO ratio until 200 ^{0}C	2.505
31- O_2consumed /m^3 rock until 200 ^{0}C (m^{3}O$_2$/m^3 rock)	12,4796
32- Air consumed m^3 /m^3 rock until 200 ^{0}C (m^3 Air/ m^3 rock)	59,4266
33- Medium speed of O_2 consumed until 200 ^{0}C (L/min)	0.5032
34- After 85.5 minutes temperature of Sample= (Oven Temp.)	115 ^{0}C

3. The temperature of burning oxygen ranged from 125^{0}C to 140 ^{0}C, which is a sufficient degree for the continuity of the ignition of oxygen consumption to complete the process successfully.

4. The rate of produced fuel "fuel availability" through laboratory tests is 47 kg/m^3. The amount of fuel produced through laboratory tests and world field, ranging 15 - 40.6 kg/m^3 and may exceed this range. These statistical results are close to those of heavy-oil fields which used thermal methods for produced fuel such as the field of Shannon which produces 49 kg/m^3 [20]. These experiments show that the amount of fuel produced decreases when the percentage of atomic hydrogen/carbon ratio increases, as well as increasing API gravity of oil. The amount of fuel produced increases when the oil viscosity and saturation of the rocks increases.

5. Laboratory tests showed that the atomic hydrogen/carbon ratio n=2.5-4.79 obtained from the combustion gases as well as through Stoichiometric reactions. This ratio decreases when the temperature increases which is n = 4 at a temperature of 270 ^{0}C, n = 2.3 at a temperature of 320 ^{0}C, and n = 0.5 at a temperature of 532 ^{0}C, whereas field tests also showed that the atomic hydrogen /carbon ratio n=0.5-1.8 [10,11,8]. The ratio is high in the low temperatures oxidation which means existence of oil.

6. Laboratory tests showed that the necessary amount of air for burning product fuel based on the partial molar ratio of the gases resulting from combustion is (5.53-7.38).

7. The initial temperature of consumed oxygen 190 ^{0}C, the CO_2 formed at temperature 225^{0}C, and the CO formed at temperature 65^{0}C. Plateau temperature started at (190-220^{0}C) until 500^{0}C with small water saturation, and air flux 23.41 cm^3/m$^{2./}$ hr.

8. The average value for the fuel availability based on several runs was 1.6889 gram carbon/100 gram rock.

9. Due to the results obtained with comparison of published results, it is possible to apply the thermal recovery methods on the reservoir (Wadi Rajil-Hamzeh oil field) at Azraq basin in Jordan.

Table 5: Showed the amount fuel availability and air required.

Initial oil saturation vol %	Fuel availability gr.C/100gr.rock at220^{0}C	Air requirement m^3/ m^{3}rock
62.5	1.8235	366.46
54.8	1.7517	376.66
52.6	1.6573	387.50
50.7	1.5234	395.5

4.1. Correlation of fuel availability with crude oil properties

Many reports were published in physical properties of crude oils, such as API gravity, viscosity, H/C ratio, and Conradson carbon. The main properties are as follow:

4. 1.1. OIL GRAVITY

Figure (4) shows how fuel availability correlates with crude oils gravity in degrees ^{0}API. The results showed that the fuel availability decreases as the API gravity of the crude oil increases.

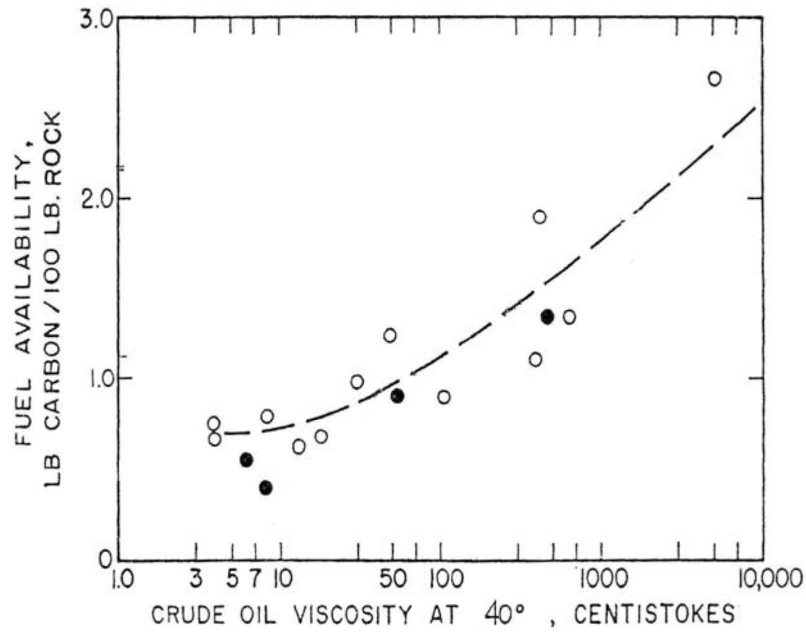

Fig. 4: Correlation of fuel availability with crude oil gravity

4.1.2. VISCOSITY

It is expected to have an increase in viscosity results and an increase in fuel availability, as shown in Figure (5). Fuel availability is due to crude oil viscosity at 40^0C.

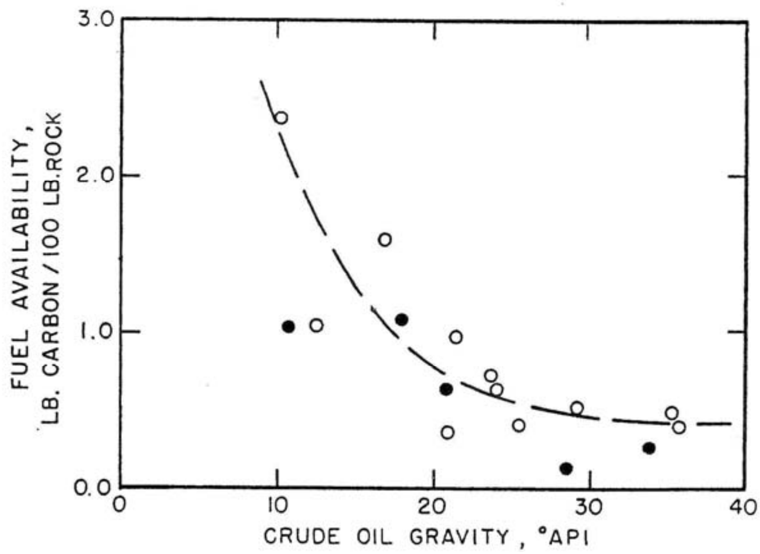

Fig. 5: Effect of crude oil viscosity on fuel availability**.**

4.1.3. ATOMIC H/C RATIO

The correlation of fuel availability with crude oils and atomic H/C ratio is shown in Fig (6), which indicates a general decrease in fuel availability as the atomic H/C Ratio of the crude oil increases. The high value of the atomic H/C ratio occurs because the oxidation reactions of hydrocarbons in crude oil at low temperature oxidation happen between 190-270^0C, and therefore the air flux is low. Laboratory tests provide a conclusion that the atomic H/C ratio is decreased as the injecting air flux increases, which is n=4.7908 at 190^0C, n =4.5978 at 225^0C, n= 3.500 at 270 ^{0}C, n =2.3 at 320^0C, n= 0.8 at 400^0C, n = 0.5 at 500^0C

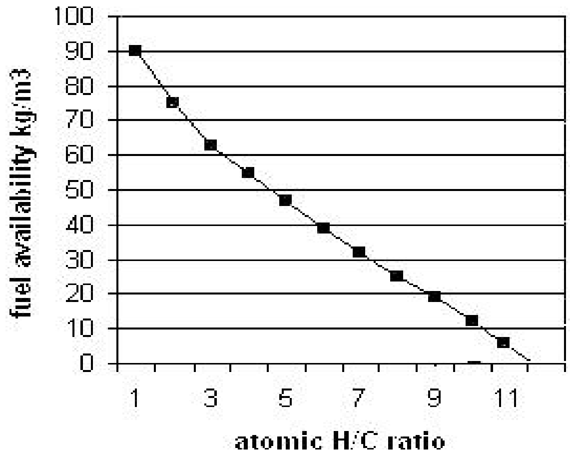

Fig. 6: : Correlation of fuel availability with crude oil H/C ratio

Table 6: Correlation of Oil density with H/C ratio

No	Reservoir	Oil density kg/m^3	H/C Ratio
1	Scheibenhard	822	1.95
2	Eaohan	865	1.75
3	—	873	1.73
4	Gabon	875	1.87
5	Soufflenheim	877	1.75
6	—	883	1.86
7	Chateaurenard	893	1.79
8	—	910	1.64
9	Talco- Texas	915	1.65
10	—	921	1.68
11	—	928	1.66
12	S.B Romania	960	1.70
13	Midway- sunset- California	967	1.56
14	—	979	1.35
15	Boscan	1000	1.55
16	H.R. Jordan	990	2.58

4.1.4. CONRADSON CARBON RESIDUE

Effects of the crude oil carbon residue on the fuel availability are illustrated in Figure (7). The results showed that the fuel availability increases due to density ,viscosity and Conradson residue, and decrease when the hydrogen/carbon ratio of the oil increases [13]. The coke–forming properties of crude oils are measured by Conradson carbon, which varies in our tests between (3.9 - 6.734 %).

Table 7: Correlation of fuel availability with Conradson carbon

Conradson Carbon%	Fuel deposit lb/100.lb rock
6.734	1.14
6.343	1.132
6.132	1.12
5.545	1.097
5.161	1.080
4.923	1.070
4.743	1.062
4.562	1.054
4.345	1.04
4	1.03
3.9	1.02

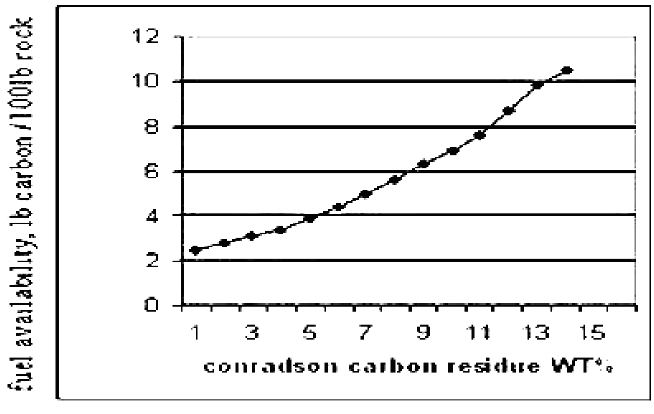

Fig.7: Effect of crude oil, Conradson carbon on fuel availability.

4.1.5. EFFECT OF LOW TEMPRETURE OXIDATION

The oxidation phenomena played an important role in the formation of petroleum cokes, natural and asphaltic bitumen [9]. Studies in the field of in-situ combustion [4, 5, 6] discussed different types of in–situ oxidation reactions and the effect of temperature. During the experiment by cell oxidation on heavy oils, oxidation process the reactions between oxygen and the fraction of oil occurring below 300C^0 are generally referred to as low temperature oxidation reactions. The test have shown that the amount of fuel deposited increased with increasing oil viscosity and carbon residue, and decreased with increasing atomic hydrogen-carbon ratio and API gravity of the oil. The effect on LTO is during the ignition phases of the in–situ combustion process. Ignition procedure can be designed to maximize LTO effects in a localized zone of several feet radius about the well ignition. Thus, we provide preheat to this zone since its level of temperature (486 ^{0}F (210^{0}C), while air is being injected at low rates. The results from the testing laboratory show that the LTO can have an important influence on the fuel availability for the in-situ combustion (low temperature oxidation) at 270^{0}C.

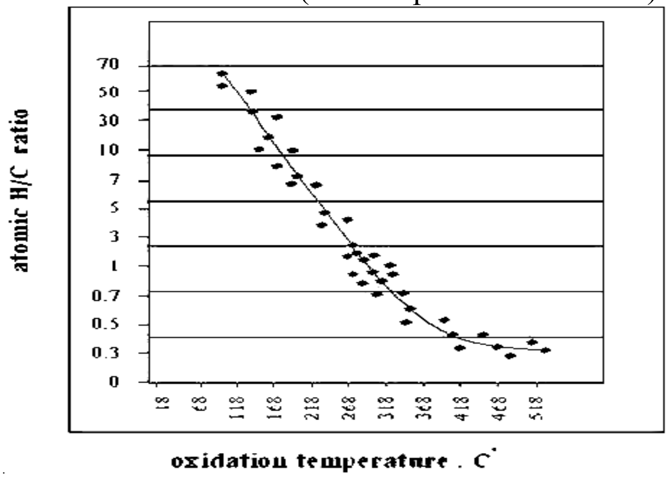

Fig. 8: Effect of temperature on apparent H/C ratio of fuel.

4.1.6. EFFECT OF AIR FLUX ON FUEL AVAILABILIY

As we can see from Figure (9), while the minimum amount of fuel availability is 13 scf/ft^2.hr, the gas fluxes varies from 13 to 23,88 scf/ft^2.hr. Also the high residual oil saturations would tend to provide fuel availability increasing, and therefore increased the amount of displaced original oil.

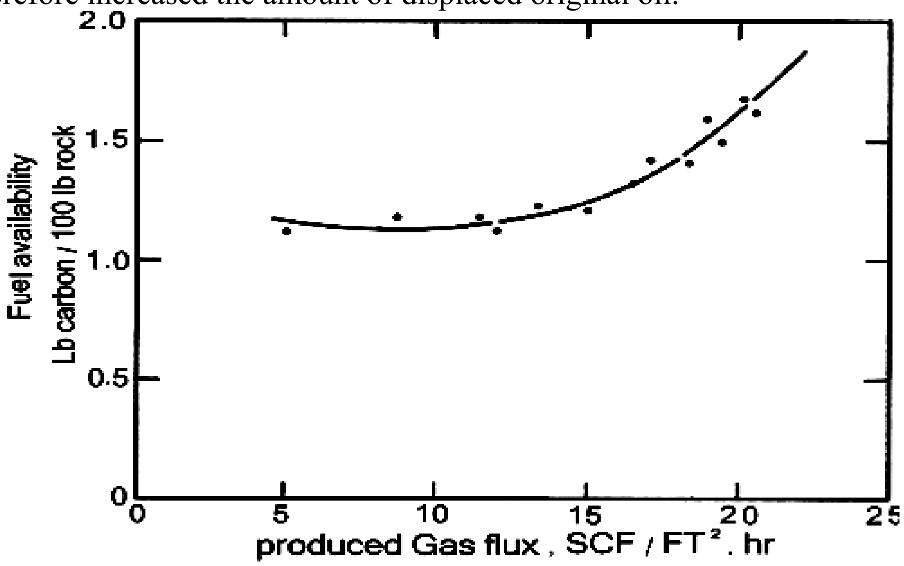

Fig 9 : effect of produced Gas flux on fuel availability

4.1.7. AIR REQUIREMENT

The air requirement depends on combustion efficiency, which means that the oxygen injected consumed and fuel formed as pounds of carbon per 100.lb of rock. The level of maximum temperature varies from 300^0C to 500^0C. The Ghareb core samples saturated with heavy crude oil and asphalt. The required air for burning one kilogram of carbon is 10.95 to 11.19 Nm^3/kg. At temperature below the 300^0C, partial oxidation reactions started, and the atomic H/C ratio increased which caused the air required to exceed the average 11.07 Nm^3/kg carbon burned. The average atomic H/C ratio of the fuel burned at a maximum combustion temperature is 420^0C ranged from (1.6 to 1.8). The fuel burned depend on the average atomic H/C ratio. In addition the average molar Co_2/Co ratios at 425^0C ranged from5.53 to7.38. Finally the fuel availability and air requirements should be determined by many runs in order to get appropriate parameters to use in field designs.

4.1.8 EFFECT OF CLAY AND METALIC CONTENT OF THE ROCKS AS INFLUENCE ON FUEL DEPOSITION

Clay and fine Sand have very high specific surface area. Studies by Fassihi et al., 1984; Vossughi et al., 1982 and Bardon and Gadelle, 1977 indicate the presence of clay and fine sand in the matrix favor increased rates of coke formation. Clay are solid acid catalysts and their catalytic actives are related to their acid site density and acid strength. Metals and metallic additives also known to affect the nature and the amount of fuel formed. It was found that various metals promote coke formation and the catalytic effect these metals Ni,V,Cu,Crs, Zn. The nickel is about four to five times as active as Vanadium (De los Rios ,1988). The rate of produced fuel "fuel availability" through laboratory tests is 47 kg/m^3. It was confirmed to various metals promote coke deposited increased rates of coke formation.

5. CONCLUSIONS

- The technique can be used to provide a basis for estimating the fuel availability and air requirements needed for engineering design for fire flood projects.
- The amount of fuel availability for in situ–combustion varies with crude oils, porous-medium characteristics, oil saturation, air flux, and time temperature relationships.
- The fuel availability decreased as the atomic H/C ratio and the API gravity of the original crude oil increased. Also the fuel availability increased as the Conradson carbon residue and the viscosity of the original crude oil increased.

- The Low temperature oxidation (LTO) prior to high temperature has a great effect on fuel availability.
- The amount of fuel availability due to laboratory test ranged from 35 to 45 kg/m^3, which is a good parameter during in situ combustion in the reservoir.
- The atomic H/C ratio of the fuel burned decreased as combustion temperature increased. This ratio for low temperature oxidation is high, but for high temperature the ratio is small.
- The total amount of air required for burning one kg carbon and its associated hydrogen with high operation temperature may be considered as constant for the crude oil and porous media.
- From the presents experimental tests , permit the application of the recovery thermal process on heavy oil /asphalt at Hamzeh- Wadi Rajel oil field on the Azraq basin in Jordan

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