Feasibility study of Borehole Gravimetry in tracking the flue gas produced from In-situ Combustion process in heavy oil field of western India.

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Keywords

Heavy oil, In-situ combustion (ISC), flue gas, borehole gravity etc.

Summary

One of the most popular ways to exploit highly viscous oil from heavy oil fields is in-situ combustion. However to optimize the recovery and locate the best possible location for drilling new wells one needs to map/track the flue gas front.
In-situ combustion produces flue gases and this gas moves forward and pushes heavy oil towards producer wells. The areas in which flue gas has encroached are marked by lowering in bulk density of rock. By use of borehole gravity measurement one can track the presence or absence of flue gas in the surrounding of a well because lower density also affects the gravitational response of layer.

Introduction

In the western region of India there is a heavy oil belt. The hydrocarbon is found, in unconsolidated reservoir having excellent reservoir properties at a shallow depth around 900m. The excellent reservoir properties are attributed to: a high-energy fluvial environment, negligible detrital or authigenic clay, insignificant diagenesis as a result of early oil migration, and poor grain packing due to shallow burial. The reservoir in unconsolidated sand is having porosities of the order of 28-30%, average permeability in the range of 3-5 darcy and water saturations at 21-26%. The average reservoir pressure and temperature are 100kg/cm2 and 70ºC respectively at a depth of 990 m below MSL. The density of crude oil is 0.95 gm/cc. Primary recovery from this field under active edge water drive was around 18%. Low primary recovery is attributed to high mobility ratio between oil and water. This necessitates the implementation of EOR method. After intensive lab studies In-situ combustion (ISC) was found to be best suited EOR method for the field.

To initiate in-situ combustion process starts with converting/ drilling a well in up dip part of reservoir. This well is used as air injector. After initiation of ignition at sand face, air is injected in pre-calculated quantity so that burning of front could be sustained. ISC process is very efficient in the sense it burns only a small quantity of oil and rest is displaced, brunt and produced from down dip producers. The process has the effect of displacing heavy oil, pressurizing the reservoir by producing flue gas cap. It also reduces viscosity of oil so that mobility ratio is improved. Figure-1 shows schematic of ISC process.
The process generates flue gas which it moves away from the fire front and the pores that were once filled with oil are now filled with oil, water and gas. This causes decrease in bulk density of reservoir rock and increase in water saturation. In this paper author has tried to evaluate the feasibility of borehole gravity analysis to trace the location flue gas cap generated from ISC process.

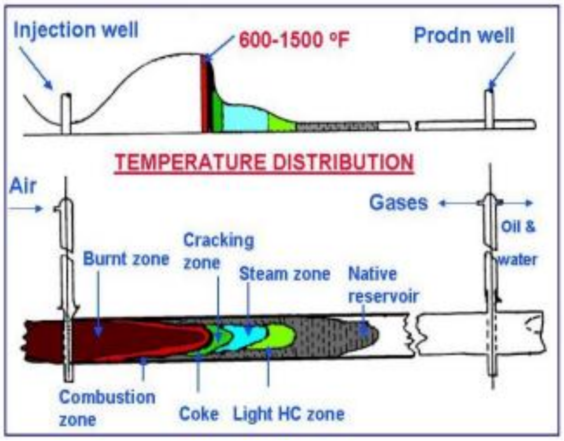


Figure 1: Schematic of In-situ combustion

Theory and/or method

Gravity method is one of the well-established geophysical exploration methods. It works on the density contrast between target and surrounding rocks. In oil industry gravity method is normally used to evaluate the thickness of sediments in a sedimentary basin. The gravity value at any point on earth is measured by Gravi-meters. These are very sensitive instruments. However since the technology has improved now borehole gravimeter (BHGM) have also came into existence. These BHGM can be put inside the well bore and can be used to measure gravity value of a layer within earth. The precession of these BHGM is around 5µgal. Borehole gravity tools have different sizes for different hole conditions. For example, tools range in diameter from 3.875 in. [98 mm] for low-temperature (110°C), low-pressure (8,000 psi) applications to 5.25 in. [133 mm] for high-temperature (204°C), high-pressure (20,000 psi) applications. The temperature range can be extended to 260°C with special ring seals.

The BHGM is useful in many aspects of oil and gas exploration and production. It is used in exploration and formation evaluation, early field development, mature field development, and enhanced oil recovery. By far, the most important Potential applications are in oil production monitoring and searching for by-passed oil and gas.

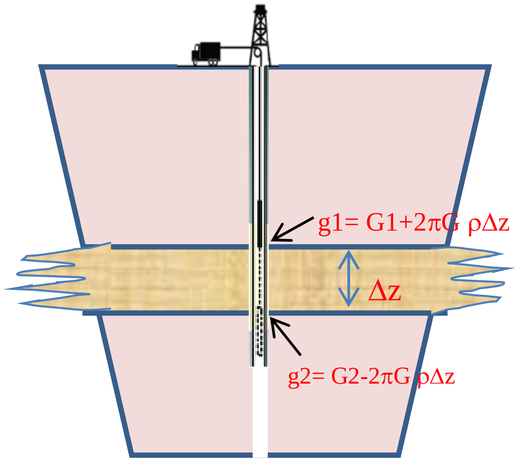


Figure 2: shows theory of obtaining bulk density from BHGM measurements

The brief theory of borehole gravimetry is as follows: The gravitational attraction, g, due to an infinite horizontal slab of rock of uniform density ρ and thickness Δz measured from any point above its upper surface is given by

$$g = 2\pi G \rho \Delta z \ldots\ldots 1$$

G, is universal gravitational constant

A borehole gravity meter placed at the upper surface of this slab figure-2 would actually read a gravity value g1 resulting from the combination of the downward slab attraction as well as the average "background" attraction caused by the Earth, G1:

$$g1 = G1 + 2\pi G \rho \Delta z \ldots\ldots 2$$

Similarly, a borehole gravity meter placed at the lower surface of this slab would actually read a gravity value g2 resulting from the combination of the upward slab attraction as well as the average background attraction at that point caused by the Earth, G2:

$$g2 = G2 - 2\pi G \rho \Delta z \ldots\ldots 3$$

The difference between two BHGM readings will give gravitational attraction by layer.

$$\Delta g = g2 - g1 = (G2 - G1) - 4\pi G \rho \Delta z$$

$$\rho = 1/(4\pi G)\,(F - \Delta g/\Delta z) \ldots\ldots 4$$

Where F is free air gradient given by:

$$F = (G2 - G1)/\Delta z \ldots\ldots 5$$

The value of free air gravity anomaly is approximated by **0.3086 mgal/m or 308.6 µgal/m**

Putting values of all the constants in appropriate units gives apparent density of layer thickness Δz as:

$$\rho = 3.6827 - 0.0119271\,(\Delta g/\Delta z) \ldots\ldots 6$$

Where,

apparent density **ρ** is in g/cc

Δg gravity difference (lower – upper) BHGM in µgal

Δz is layer thickness in meters.

In the present analysis Eq.6 is rearranged to calculate gravity gradient in layer as:

$$\Delta g/\Delta z = 308.76 - 83.84\,\rho \ldots\ldots 7$$

Eq. 7 is used to forward model differential gravity value that would be read by BHGM placed on top and bottom of a layer of given thickness **Δz**.

Calculated differential gravity values were inverted back to predict the change in density due to flue gas incursion. This density change can be attributed to position of flue gas cap.

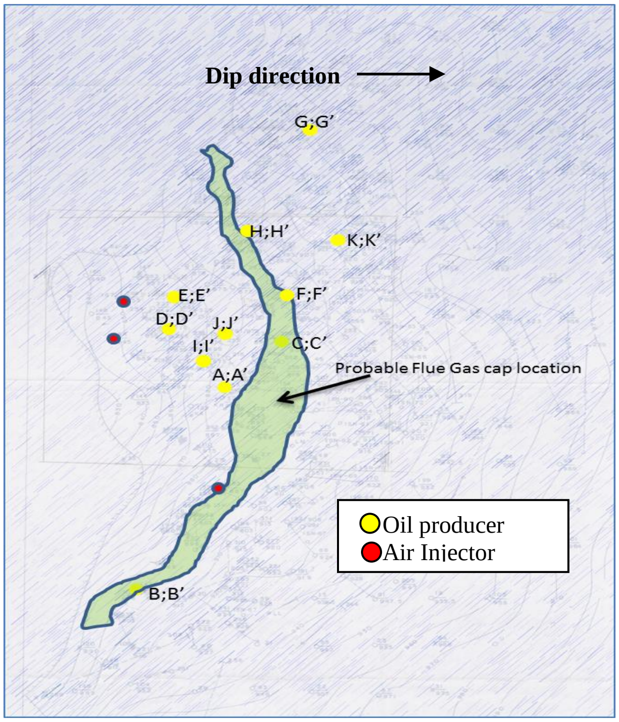


Figure: 3 Location of wells used in study

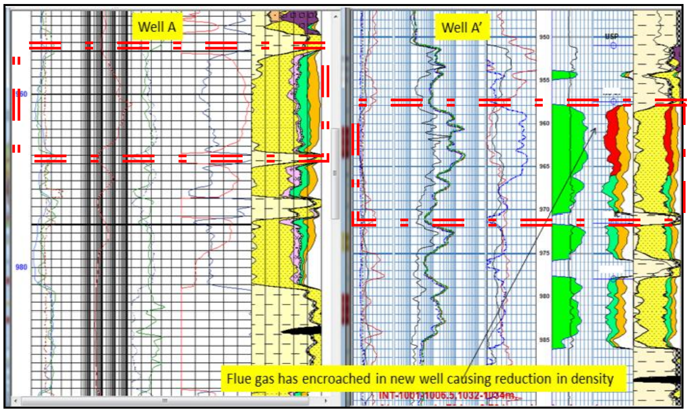
Workflow

- Very closely spaced pair of wells is taken for study area in order to calculate effect of flue gas on gravity value.
- The well spacing between a pair of wells varies from 11m to 37m. Hence, for all practical purposes of this study they are considered to be a single well with logs in old well as base reading before ISC process and logs in new well as repeat reading. Also in each pair one well is drilled before ISC so it is not affected by ISC and other one is drilled after ISC so may or may not have effect of ISC depending on whether flue gases has reached to it or not. Average of density **ρ** and **Sw** were calculated for reservoir XX from old and new logs.
- In each pair of wells Gravity gradient of old well is used as base value of gradient and of new well as repeat value of gradient at a location. This gravity gradient **$\Delta g/\Delta z$** is used to calculate final **Δg** at a particular location.
- This **Δg** is the value of the gravity difference that would be given by pair of BHGM placed at the top and bottom of reservoir.
- Now change in **Δg** is calculated from base and repeated values
- Linear relation between density and gravity value change **$\delta(\Delta g)$** with time is established and new density is predicted and compared with repeat value of density.
- Linear relation between density and **Sw** change with time is established and new **Sw** is predicted.

In the present study the effort was to evaluate the change in theoretical borehole gravity value before and after the ISC in order to track the flue gases produced from ISC process. For this study 11 pair of wells is chosen. In each pair old well represent the sample before ISC and new well after ISC. The probable flue gas cap is about 890-900m depth. The pairs are chosen in such a way that a few newer well of the pairs are within flue gas regime and other outside the flue gas cap. The location of the pairs is given in figure-3. Yellow locations are the location of pairs used in study and red one are the air injectors. The green area shows the probable limit of flue gas cap. Well pair G; G' and K; K' are outside the probable flue gas cap area. Well A to K are taken as base wells of each pair and A' to K' are repeated ones.

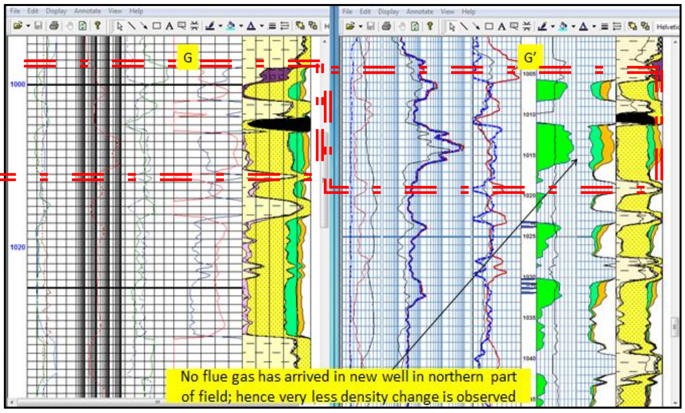
Table-1 shows the change in density and water saturation at a location due to ISC process.

- It is observed that in most the pair of wells which are



Flue gas has encroached in new well causing reduction in density

Figure: 4 Shows flue gas incursion in well A' after ISC process



No flue gas has arrived in new well in northern part of field; hence very less density change is observed

Figure: 5 Well pair G; G' is outside flue gas cap region.

falling within the flue gas cap region density is decreasing with time. The pore space which was earlier filled by oil is now filled with oil, water and/or gas figure-4&5.

- Now using Eq.-7 the base and repeat density at each location is translated into base and repeat gravity gradient respectively.
- These gravity gradients are translated into base and repeat value of theoretical differential gravity **Δg** that a BHGM pair would have read table -2.
- **$\delta(\Delta g)$** is difference of this repeat **Δg** with base **Δg** and represents the change in gravity value which is caused by change in reservoir fluid properties.
- At locations where flue gas has encroached the change in gravity value **$\delta(\Delta g)$** are large and the locations which are outside probable flue gas cap zone have very less change in **Δg.**
- In this way by taking the base and repeat reading of gravity one can point out whether the gas cap has reached into the surrounding of that location or not.

In another part of the study, the change in differential gravity **$\delta(\Delta g)$** is used to predict the density.

- For this linear relation between change in differential gravity **$\delta(\Delta g)$** and in density **$\delta\rho$** with time is established figure -7.

  $\delta\rho = 0.0014\,\delta(\Delta g)$………… ……………………..8

  So predicted value of density at a location is given by

  $\rho_{predicted} = \rho_{base} - 0.0014 * \delta(\Delta g)$……………………..9
- Table-2 shows the predicted value of density calculated using Eq.9.
- The predicted density has maximum error of 13%. If more data points are used in regression fit the error can be minimized.

In this way the change in differential gravity reading with time can be used to predict density which in turn can be associated with saturation change due to ISC process.

In the next part of study change in density with time is related with water saturation in the flue gas cap area.

- It is observed that the water saturation of the new wells is more than the older ones.
- In a few pairs decrease in water saturation with time

S.N.	Well	Spud date	Distance between wells	Layer top	Layer bot	Thickness (m)	Avg layer density (g/cc)	$\delta\rho$ (base-repeat)	Sw	δSw (base-repeat)	$\Delta g/\Delta z$ (μgal/m)
1	A'	10/15	12	957.51	968.39	10.88	1.966	0.157	0.28	-0.11	143.15
	A	06/94		955.44	966.58	11.14	2.123		0.17		130.03
2	B'	07/09	11	969.46	977.26	7.8	1.985	0.235	0.49	-0.17	141.58
	B	10/86		971.88	980.13	8.25	2.220		0.32		121.87
3	C'	10/12	27	972.84	984.73	11.89	2.065	0.049	0.51	0.24	134.85
	C	01/95		968.39	978.4	10.01	2.114		0.76		130.74
4	D'	12/12	20	931.26	940.24	8.98	1.961	0.181	0.35	-0.19	143.59
	D	08/94		927.65	935.97	8.32	2.142		0.15		128.41
5	E'	10/10	27	934.21	941.31	7.1	1.976	0.129	0.37	-0.18	142.33
	D	12/97		930.29	937.09	6.8	2.105		0.19		131.50
6	F'	12/10	11	972.19	982.11	9.92	2.016	0.115	0.38	-0.06	138.96
	F	06/94		970.93	981.41	10.48	2.131		0.32		129.35
7	G'	06/12	33	1011.17	1016.86	5.69	2.087	0.021	0.25	0.04	133.01
	G	11/85		1005.65	1012.84	7.19	2.108		0.29		131.23
8	H'	07/09	15	979.94	989.87	9.93	2.104	0.044	0.70	-0.23	131.56
	H	04/86		980.02	989.03	9.01	2.149		0.47		127.85
9	I'	05/14	37	945.48	952.23	6.75	1.918	0.169	0.26	-0.12	147.17
	I	07/86		943.48	952.78	9.3	2.088		0.14		132.98
10	J'	09/10	13	947.582	956.22	8.6376	1.954	0.186	0.40	-0.23	144.18
	J	08/94		944.87	952.25	7.38	2.140		0.17		128.55
11	K'	09/08	11	965.35	972.67	7.32	2.120	0.002	0.82	-0.49	130.26
	K	04/87		964.31	971.93	7.62	2.122		0.33		130.12

Table-1: Basic data calculated from well logs

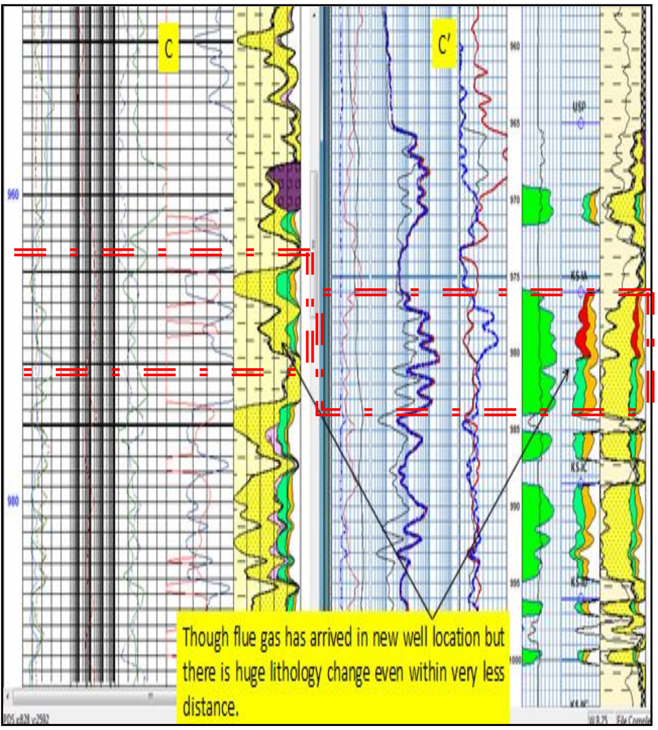


Figure: 6 Well pair C; C’: Shale in well C becomes sand in C’ cause better oil saturation in new well

is also observed. This is a contrary observation. It is because of the fact that although for the purpose of study two closely spaced wells are treated as single well with repeat reading but in some case there is large change in reservoir facies even within this very small distance. For example if a sand in new well becomes shale in old well, than average water saturation in old well will be higher than new well. Figure -6 shows this phenomenon. Change in facies within very short distance causing abnormal behavior in change in water saturation.

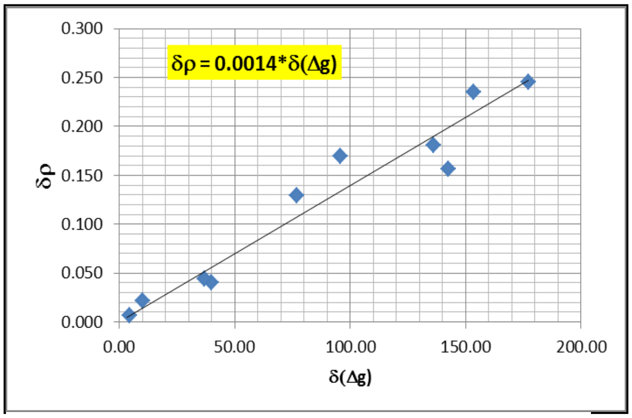


Figure-7 Plot of δ(Δg) vs. δρ

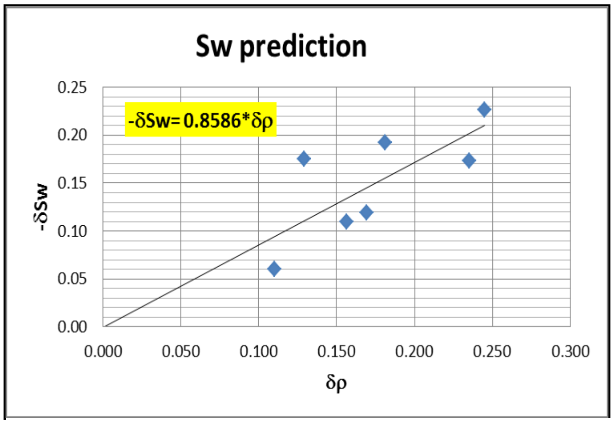


Figure-8 Plot of δρ vs. δ(ΔSw)

- Again a linear relation between changes in water saturation with density for wells in flue gas regime is established by plotting change in density along x-axis and change in water saturation along y-axis. As shown in figure-8.

Well location	Layer thickness	Base density (g/cc)	Repeat density(g/cc)	δρ	Base Sw	Repeat Sw	δ Sw	Base Δg/Δz (μgal/m)	Repeat Δg/Δz (μgal/m)	Base Δg (μgal)	Repeat Δg (μgal)	δ(Δg) (μgal)	$\rho_{predicted}$	% error in density prediction
A;A'	10.88	2.123	1.966	0.157	0.17	0.28	-0.11	130.79	143.91	1423.01	1565.76	142.76	1.766	10.165
B;B'	7.8	2.220	1.985	0.235	0.32	0.49	-0.17	122.63	142.34	956.52	1110.22	153.70	1.770	10.840
C;C'	11.89	2.110	2.070	0.040	0.76	0.51	0.25	131.86	135.21	1567.79	1607.66	39.87	2.014	2.697
D;D'	8.98	2.142	1.961	0.181	0.15	0.35	-0.19	129.17	144.35	1159.99	1296.27	136.28	1.770	9.730
E;E'	7.1	2.105	1.976	0.129	0.19	0.37	-0.18	132.26	143.09	939.04	1015.93	76.89	1.868	5.448
F;F'	9.92	2.130	2.020	0.110	0.32	0.38	-0.06	130.18	139.40	1291.39	1382.88	91.49	1.892	6.341
G;G'	5.69	2.108	2.087	0.021	0.29	0.25	0.04	131.99	133.77	751.00	761.14	10.14	2.073	0.680
H;H'	9.93	2.149	2.104	0.044	0.47	0.70	-0.23	128.61	132.32	1277.06	1313.98	36.92	2.053	2.456
I;I'	6.75	2.088	1.918	0.169	0.14	0.26	-0.12	133.74	147.93	902.76	998.53	95.77	1.784	6.990
J;J'	8.6376	2.140	1.895	0.245	0.17	0.40	-0.23	129.31	149.86	1116.96	1294.47	177.51	1.647	13.112
K;K'	7.32	2.127	2.120	0.007	0.33	0.81	-0.48	130.43	131.02	954.76	959.06	4.30	2.114	0.284

Table-2 Calculation of gravity change and density prediction

Well location	Layer thickness	Base density (g/cc)	Repeat density(g/cc)	$\delta\rho$	Base Sw	Repeat Sw	δ Sw	$Sw_{predicted}$	% error in Sw prediction
A;A'	10.88	2.123	1.966	0.157	0.17	0.28	0.11	0.305	8.760
B;B'	7.8	2.220	1.985	0.235	0.32	0.49	0.17	0.518	5.819
D';D	8.98	2.142	1.961	0.181	0.15	0.35	0.19	0.309	10.529
E;E'	7.1	2.105	1.976	0.129	0.19	0.37	0.18	0.304	17.529
F;F'	9.92	2.130	2.020	0.110	0.32	0.38	0.06	0.414	9.065
I;I'	6.75	2.088	1.918	0.169	0.14	0.26	0.12	0.284	10.200
J;J'	8.6376	2.140	1.895	0.245	0.17	0.40	0.23	0.380	3.962
K;K'	7.32	2.127	2.120	0.007	0.33	0.81	0.48	Well outside gas cap region	
G;G'	5.69	2.108	2.087	0.021	0.29	0.25	-0.04		
H;H'	9.93	2.149	2.104	0.044	0.47	0.70	0.23		
C;C'	11.89	2.110	2.070	0.040	0.76	0.51	-0.25	facies change	

Table-3 Prediction of water saturation from density change due to flue gas incursion.

- The relation comes out to be:
  $-\delta Sw=0.8586*(\delta\rho)$……………………………….10
  $Sw_{predicted}=Sw_{base} + 0.8561*(\delta\rho)$………………....11

Table-3 shows the predicted water saturation calculated from Eq.11 and error in prediction. Maximum error in prediction is 17%. Four pairs have not been included in analysis because it is either outside flue gas cap reason or there is large change in facies within very short distance.

Conclusion

This work effectively brings out that even in absence of base reading of bore-hole gravity, through theoretical well log measurements from close by old and new wells, change in gravity gradient hence gravity can be calculated and this change can be used to track flue gas front. As the incursion of flue gas produced from ICS process causes lowering of density hence measurable change in gravitational pull of the reservoir layer is observed. If repeated in appropriate time interval BHGM can be effectively used to track the position of flue gas cap. However, the availability of the well can be an issue in the operational applicability of the bore-hole gravimetry. Since the depth of penetration of BHGM is about 4-5 time layer thickness it can also be used to predict density and water saturation around the well.

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