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Electrical Wellbore Heating in Environmentally Sensitive Llancanelo Field, Argentina

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Abstract

Steam injection processes were abandoned due to environmental regulations in Llancanelo heavy oil field. This reservoir consists of a series of interbedded sandstone and conglomerates in cretaceous aged Neuquen Group. Down-hole electrical well bore heating technique, which is insensitive to the environmental regulations, was implemented. Despite that electrical heating for heavy oil reservoirs are established methods for in situ viscosity reductions, the commercialization and wider application of this heating technique required detailed analyses to determine optimal application conditions in horizontal well trajectory design for a heterogeneous reservoir.

Recovery factor obtained with natural depletion was less than 0.2%. Viscosity and temperature relationship was the most critical parameter to determine the applicability of the project in the productive interval. In this paper, it has been shown that electrical well bore heating can be an alternative in this environmentally sensitive reservoir with two different oil viscosity layers; Green zone with 11200 cp and Olive zone with 3880 cp at the surface conditions.

The impact of the different heating temperature and heating time on additional oil recovery were analyzed for the reservoir rock and fluid properties. Detailed simulation runs were conducted to understand recovery mechanism of convective and thermal conductive processes for well heating. By increasing the well bore temperature from initial 56 °C to 100 °C, the following results were obtained;

1- An additional oil recovery for Olive zone can be increased up to 110%, on the other hand an additional oil recovery for Green zone can be increased up to 62%, respectively.
2- Energy consumption of 1 MM BTU for Olive zone will lead an additional oil recovery of 6 STB, whereas 1 MMBTU consumption for Green zone will lead an additional oil recovery of 3 STB.
3- Energy rate per horizontal length is in range of 40–60 Watt/ft per the Green zone.
4- Well bore heating will not change the reservoir temperature and viscosity of the oil beyond 30 m far away.

In this paper, it has been shown that electrical well bore heating was economically viable in environmentally sensitive and heterogeneous reservoirs.

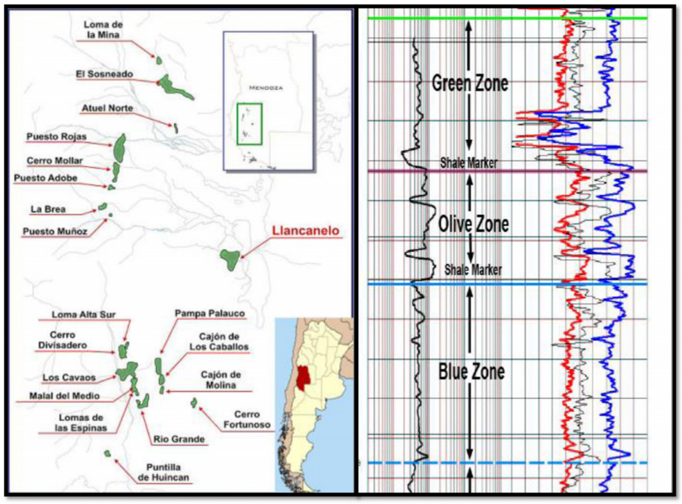

Figure 1—Field Location and Productive Zones.

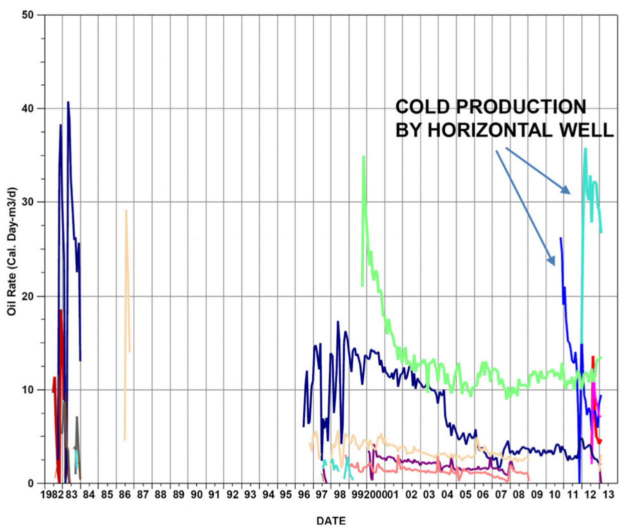

Figure 2—Historical Production Profiles.

Introduction

The Llancanelo field is located in the southern part of Mendoza province, Argentina, approximately 400 kilometers south of the city of Mendoza, Fig. 1. It was filled with Jurassic and Cretaceous marine sediments of Pacific origin. The main zone of interest is cretaceous age Neuquén Group which includes of a series of interbedded sandstones and conglomerates with a thicknesses ranging from 150 to 300 meters. Deposited in an alluvial fan environment, the individual sand units are very difficult to correlate laterally from well to well. Series of regional shale markers do allow the Neuquén to be subdivided into three separate reservoir zones as shown in Fig. 1, (YPF Llancanelo Report). The three reservoir zones are the Green, Olive and Blue Zones with the two main heavy oil bearing zones with API of 12 to 14 ranges being the Green and the Olive.

Oil has been discovered in the Llancanelo area since 1930. However, most operations have been of small-scale. Steam injection was implemented in the years 1984 and 1985 in a few wells. Due to economic and technical reasons, steam injection was abandoned in 1985, Fig. 2.

A court-ordered suspension of the proposed project in 2001 prevented expansion of oil operations in the area until Llancanelo Reserve boundaries could be established. The Laguna Llancanelo is an extensive salt-water lagoon located in a semi-desert environment. Lagoon and surrounding wetland area are species rich and inhabited by different species. Laguna Llancanelo and some of the surrounding area were added to the list of Wetlands of International Importance in November 1995, Fig. 3.

The project of steam injection of thermal recoveries was denied on the grounds that the protection of the environment should take priority over the rights of companies. Due to environmental restrictions on surrounding area and deterioration of surface and underground reservoir, conventional thermal methods were not allowed. Therefore, non-conventional, e.g. electrical techniques are being investigated to enhance the production of heavy oil reservoir.

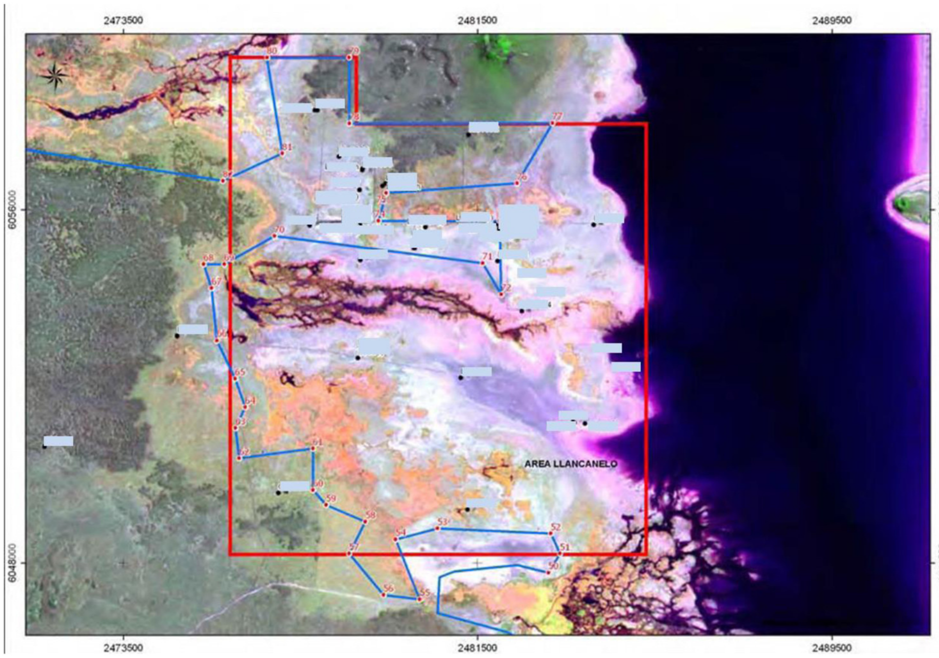

Figure 3—National Park and Surface Access Limitations.

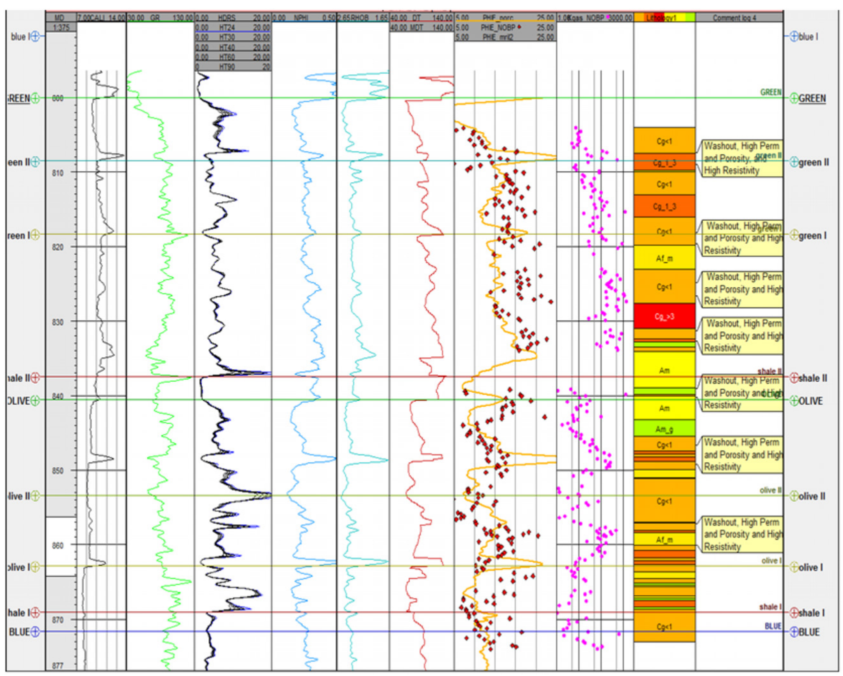

Figure 4—Productive Intervals of High Porosity, Permeability, and High Resistivity.

It has been reported that electrical heating methods have been better in terms of the depth of the reservoir and controlling the heat losses, (Rangel-German 2007, Gasbarri 2011) and they can be implemented with high efficiency, low initial investment cost and in a short period. Heat loss during steam flow in surface pipes and tubings, effect of condensed water-oil flow on oil production in conventional steam injection processes are not exhibit in electrical well bore heating processes (Mohsin 2012). Production arrangement, transportation and storage systems are similar to the cold production; therefore no additional investment is required in facilities. Electrical heating methods can achieve higher efficiency in heterogeneous reservoir environment as compared with any thermal flooding, (Carrizales and Lake,

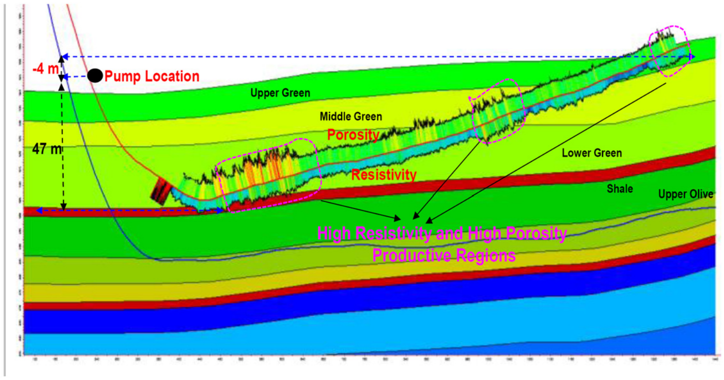

Figure 5—Horizontal Well Bore Configuration.

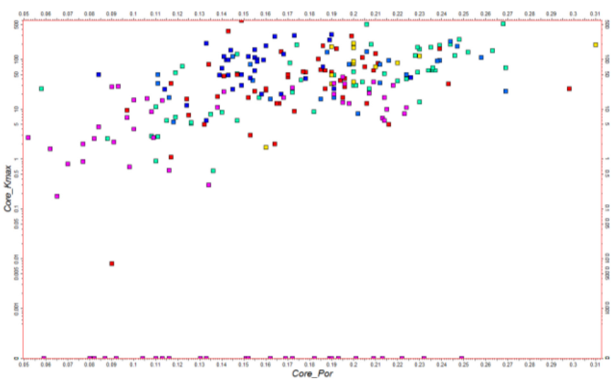

Figure 6—Measured Core Permeability and Porosities.

2009). Another benefit of using electrical heating is that the energy can be applied directly into the area of productive zone, (Chakma and Jha, 1992). Electrical well bore heating have also been considered along with other thermal method such assisted gravity gas injection derive mechanism, (Zhong, 2011).

Down hole electric heating methods have been divided into three categories. Low-frequency electric current methods are classified as Ohmic or resistive heating. High-frequency electric current are used for microwaves or radio frequency methods. Low-Medium frequency current method is induction-heating method (Hascakir, 2010).

Downhole heater system that is used in Llancanelo well has three main parts; power connection compound, power cable and heating cable. Heating cable can be inside tubing or annulus for vertical wells or along the horizontal well bore section. Heat generated inside well bore by heating cable will reduce the oil viscosity and density for better lifting. Heat generated near well bore formation will reduce oil viscosity and thermal expansion of fluids through thermal conduction by casing, formation rock, and fluids. Downhole well bore heating process is kind of permanent well stimulation technique with negative skin effect.

This paper investigates the technical feasibility and economic potential of employing the electrically well bore heating for environmentally sensitive area and heteregenous reservoir. For this purpose, first, well trajectory configuration, rock and fluid properties of simulated wells will be described. Then, by setting well bore temperature to different temperatures from 56 °C to 120 °C, incremental oil productions, well bore temperature, pressure, and viscosity profiles will be analyzed for different productive zones. Next, cumulative energy cost and energy rate per horizontal well lengths are presented for economic analysis. Finally, discussion and conclusion of well bore heating are presented for environmentally sensitive and heteregenous reservoir.

Reservoir and PVT Properties

LLancanelo reservoir properties are representing heteregenous reservoir properties rather than any conventional homogenous, shallow, high porosity and permeability reservoirs. Series of interbedded sandstones and conglomerates have high permeability and porosity at the base of each cycle due to sedimentation of coarser conglomerates and sands, Fig. 4.

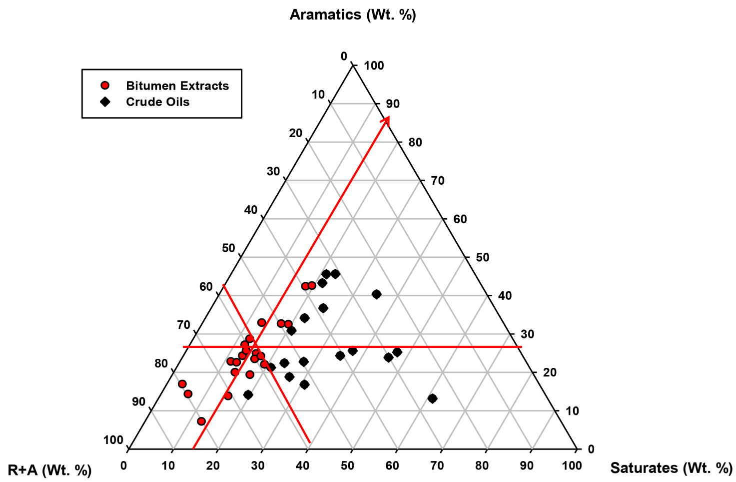

Figure 7—SARA Composition.

Table 1—PVT Data and Thermal Properties

PVT DATA	
Initial Reservoir Pressure (Kg/cm2)	90
Initial Reservoir Temperature °C	56
Oil Density (gr/cm3)	0.978
Bubble Point Pressure (Kg/cm$^{2)}$	39
Solution Gas Oil Ratio (SCM/SCM)	8
SARA COMPOSITION	
Saturated Hydrocarbon (Mol %)	24.9
Aromatic Hydrocarbon (Mol %)	
Resin (Mol %)	
Asphaltene (Mol %)	
THERMAL PROPERTIES	
Thermal Cunductivity of Rock (J/m/day/C)	1.496E+05
Thermal Cunductivity of Oil (J/m/day/C)	0.0115
Thermal Cunductivity of Water (J/m/day/C)	0.0527

A vertical pilot well was used to determine the horizontal well trajectory as shown in Fig. 4. The well configuration of horizontal well was chosen to be in J shape at base of Lower-Green zone, as shown in Fig. 5. For heavy oil and unconsolidated environments, J shape horizontal well bore configuration can reduce possibility of well bore deposition, accumulations, and reduce the pressure drop along the horizontal well bore.

When LWD logs in horizontal well are analyzed and compared to the vertical well logs, high porosity and resistivity logs responses were observed at the base of the each cycle in the Green zone. As shown in vertical well in Fig. 3, high porosity and resistivity logs responses were also observed at the base of the each cycle. By determining the productive high productive intervals along the horizontal well bore, selective heating zones or selective temperature profiles can be implemented along the horizontal well bore.

Electrical heating methods can achievehigher efficiency in heterogeneous reservoir when the reservoir has variable ranges of permeability and porosity with non-continuous productive environment; compare to conventional thermal recovery methods. As shown in Fig. 6, measured core permeabilities are in range of 10 to 600 mD, and porosities are in range of 10% to 28%.

Sara composition analysis has shown that the content of asphaltene, resin, aromatic, and saturated are 10.95%, 26.09%, 36.59%, and 24.29%, respectively. When the LLancanelo SARA analysis is compared to similar published field data, it can be observed that LLancanelo oil composition is in the transition of heavy oil and Bitumen zone as shown in Fig. 7.

Basic PVT, rock and fluid thermal properties are shown in Table 1. Heavy oil density is 0.978 gr/cm^3, (13 °API). The reservoir has initial pressure of 90 Kg/cm^2 and initial reservoir temperature is 56 °C. The bubble point pressure from PVT experiment is 39 Kg/cm^2 with the solution gas oil ratio of 8 SCM/SCM and formation volume factor of 1.045. The most important critical parameter for this study is measured viscosity and temperature data. Dead oil samples from Olive and Verde productive zones were taken and their viscosities were measured at the different temperatures with different share rates. Olive and Green

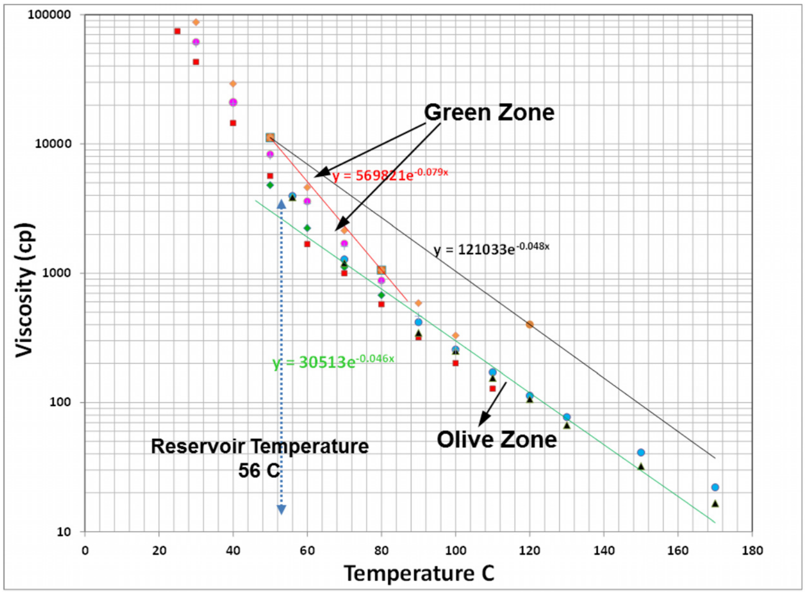

Figure 8—Viscosity and Temperatures.

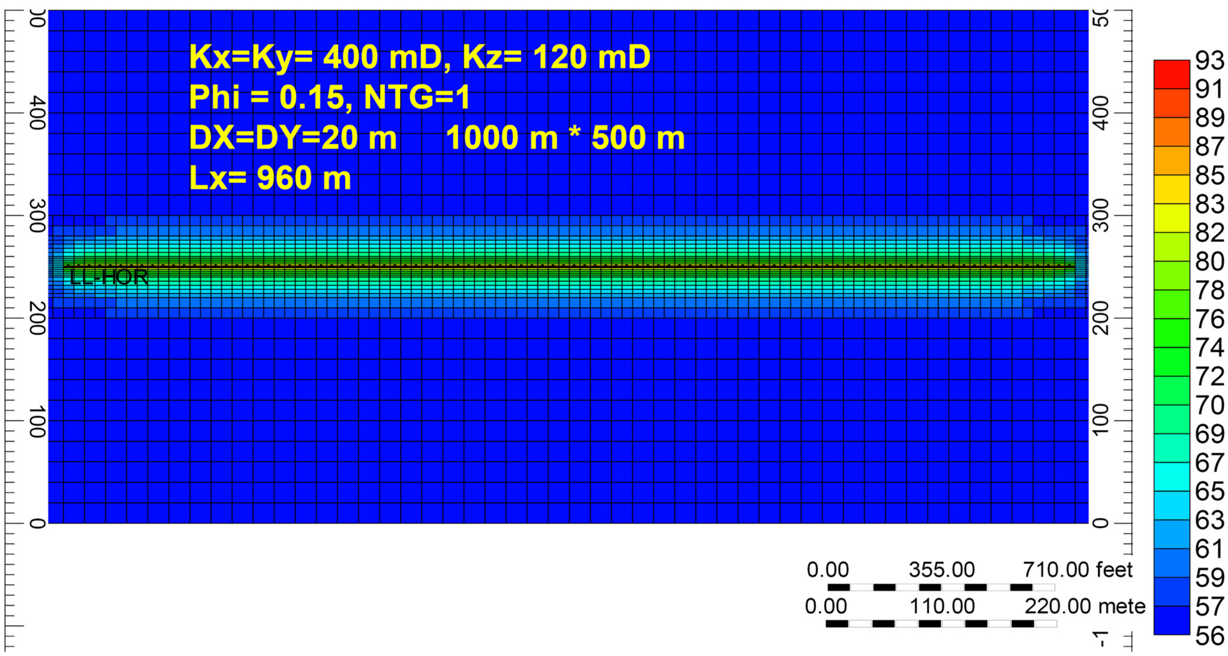

Figure 9—Simulation Grid Design and Temperature Distribution.

zones have very different viscosity values. Dead oil viscosity at the reservoir temperatures is 3880 cp for Olive zone, and 11200 cp for Green zone, respectively. All available measured viscosity data and its correlations are presented in Fig. 8.

Downhole electrical heating method was first designed in Verde unit. As shown in Fig. 8, by raising the well bore temperature from 56 °C to 120 °C, oil viscosity can be reduced from 11200 cp to 440 cp. Viscosity reduction by temperature rise is almost two-magnitude orders.

The selected candidate well was under cold production in the first year. As shown in Fig. 2, the initial oil rate was a 25 SCM/D and it was stabilized at around 6 SCM/D. The main objective of this study is to determine optimal application conditions of electrical heating for described reservoir and its fluid

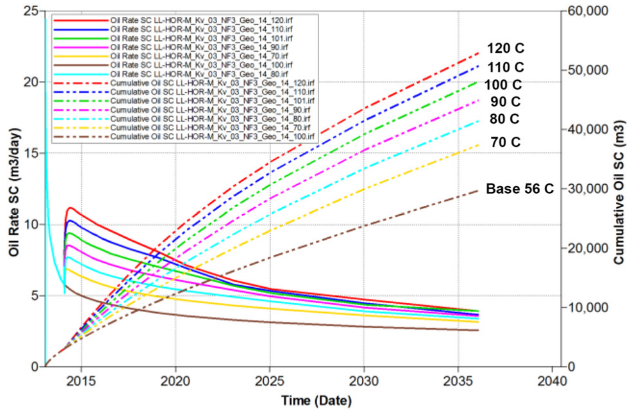

Figure 10—Oil Rates and Cumulative Oil Productions for Different Temperatures.

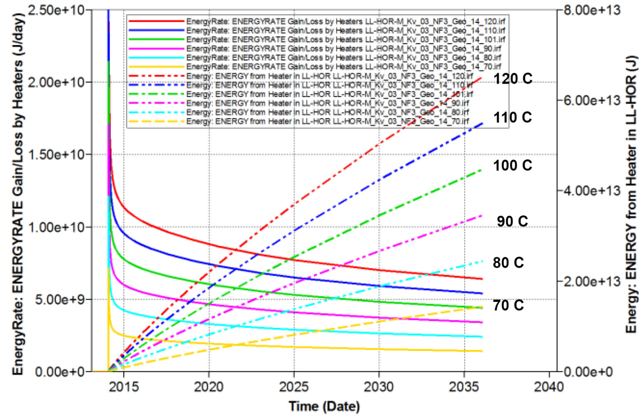

Figure 11—Emery Rates Consumptions. and Cum. Energy Consumptions for Different Temp.

Table 2—Incremental Oil Production, Cumulative Energy Cost, and Energy Rate per Length for Green Zone

Base Case	Additional Oil Recovery ΔNp						Cumulative Energy Cost (STB/ MM BTU)						Energy Rate						Energy Rate per Length					
56 C	70 C	80 C	90 C	100 C	110 C	120 C	70 C	80 C	90 C	100 C	110 C	120 C	70 C	80 C	90 C	100 C	110 C	120 C	70 C	80 C	90 C	100 C	110 C	120 C
Np	SCM	SCM	SCM	SCM	SCM	SCM							kW	kW	kW	kW	kW	kW	Watt/ft	Watt/ft	Watt/ft	Watt/ft	Watt/ft	Watt/ft
0.0																								
24.4																								
271.3																								
470.6																								
826.1																								
1112.0																								
1376.7																								
1613.6																								
1843.6																								
2061.2																								
2262.0																								
2460.1																								
2643.7																								
2827.7																								
3007.5	0	0	0	0	0	0																		
3167.1	28	46	64	81	100	117	1.72	1.65	1.61	1.59	1.59	1.58	45	77	109	141	173	205	14	25	35	45	55	65
3340.7	67	109	152	193	235	277	2.13	2.05	2.02	1.97	1.95	1.94	37	63	89	113	139	165	12	20	28	36	44	52
3506.1	106	174	242	308	376	443	2.37	2.29	2.25	2.22	2.20	2.18	34	58	82	106	129	154	11	18	26	34	41	49
3674.2	147	242	337	431	526	621	2.54	2.46	2.42	2.39	2.38	2.36	33	56	79	102	124	147	10	18	25	32	40	47
3834.6	188	310	429	551	673	794	2.67	2.59	2.55	2.52	2.50	2.49	32	54	76	99	121	144	10	17	24	31	38	46
3998.1	230	379	526	675	825	974	2.78	2.69	2.65	2.62	2.61	2.60	31	53	75	96	118	140	10	17	24	31	38	45
4159.3	272	448	623	799	977	1154	2.87	2.78	2.73	2.71	2.69	2.68	30	52	73	95	116	138	10	16	23	30	37	44
4313.8	314	515	717	919	1124	1326	2.94	2.84	2.80	2.77	2.76	2.74	30	51	72	93	114	136	9	16	23	30	36	43
4471.8	355	585	813	1043	1274	1504	3.00	2.90	2.86	2.83	2.81	2.80	29	50	71	92	113	134	9	16	23	29	36	43
4623.2	396	651	905	1162	1419	1675	3.05	2.95	2.90	2.88	2.86	2.84	29	50	70	91	112	133	9	16	22	29	35	42
4778.2	438	720	1001	1283	1567	1851	3.10	2.99	2.94	2.92	2.90	2.88	29	49	69	90	110	131	9	16	22	29	35	42
4931.8	480	787	1096	1403	1715	2026	3.14	3.03	2.98	2.95	2.93	2.92	29	49	69	89	109	130	9	15	22	28	35	41
6639.8	953	1558	2162	2784	3410	4025	3.39	3.26	3.20	3.18	3.16	3.14	26	45	64	82	101	120	8	14	20	26	32	38
8219.9	1397	2294	3187	4099	5021	5912	3.47	3.35	3.29	3.27	3.25	3.23	25	43	60	78	96	114	8	14	19	25	30	36
9693.0	1834	2997	4178	5360	6546	7681	3.55	3.41	3.35	3.32	3.30	3.26	24	41	58	75	92	109	8	13	18	24	29	35
11097.3	2253	3680	5126	6561	7979	9309	3.59	3.45	3.39	3.35	3.31	3.25	23	39	56	72	89	105	7	12	18	23	28	33
12435.8	2666	4346	6037	7715	9318	10748	3.63	3.48	3.41	3.36	3.30	3.21	22	38	54	70	86	102	7	12	17	22	27	32
13726.0	3064	4992	6920	8790	10511	12059	3.65	3.50	3.42	3.36	3.26	3.15	22	37	52	68	83	98	7	12	17	21	26	31
14964.5	3461	5622	7760	9786	11603	13200	3.68	3.52	3.43	3.34	3.22	3.08	21	36	51	66	81	96	7	11	16	21	26	30
16177.1	3834	6217	8547	10676	12568	14258	3.69	3.52	3.42	3.30	3.15	3.01	21	35	50	64	79	93	7	11	16	20	25	30
17345.9	4208	6799	9282	11517	13498	15218	3.71	3.52	3.40	3.25	3.10	2.95	20	34	48	63	77	91	6	11	15	20	24	29
18496.9	4563	7352	9958	12283	14324	16128	3.71	3.52	3.37	3.21	3.04	2.88	20	33	47	61	75	89	6	11	15	19	24	28
19616.5	4909	7869	10590	13001	15111	16958	3.72	3.50	3.33	3.16	2.99	2.82	19	33	46	60	74	87	6	10	15	19	23	28
20705.3	5248	8365	11184	13666	15839	17716	3.72	3.49	3.29	3.11	2.93	2.76	19	32	45	59	72	85	6	10	14	19	23	27
21772.6	5577	8830	11748	14304	16536	18406	3.72	3.46	3.26	3.06	2.88	2.70	19	32	45	58	71	84	6	10	14	18	22	27
22827.8	5887	9268	12267	14893	17158	19090	3.71	3.43	3.21	3.01	2.82	2.65	18	31	44	57	70	82	6	10	14	18	22	26
23854.6	6188	9678	12766	15456	17729	19806	3.70	3.40	3.17	2.97	2.77	2.61	18	31	43	56	68	81	6	10	14	18	22	26
24867.8	6471	10068	13236	15967	18336	20531	3.69	3.37	3.13	2.92	2.73	2.57	18	30	42	55	67	80	6	10	13	17	21	25
25859.9	6740	10442	13683	16459	18939	21237	3.67	3.34	3.09	2.87	2.69	2.54	17	30	42	54	66	79	6	9	13	17	21	25
26842.2	6998	10787	14102	16947	19570	21779	3.64	3.30	3.05	2.83	2.66	2.50	17	29	41	53	65	77	5	9	13	17	21	25
27806.8	7242	11125	14491	17428	20143	22254	3.62	3.27	3.01	2.80	2.63	2.45	17	29	41	52	64	76	5	9	13	17	20	24
28756.7	7470	11445	14875	17912	20612	22702	3.59	3.24	2.97	2.77	2.59	2.41	17	28	40	52	63	75	5	9	13	16	20	24
29692.2	7690	11748	15227	18404	21016	23197	3.56	3.20	2.93	2.74	2.55	2.37	16	28	39	51	63	74	5	9	13	16	20	24

properties. For this purpose, different simulation models were constructed for optimum temperature boundary conditions for Green and Olive zones.

Simulation Model for Green Zone

A detail near wellbore simulation modeling is another key parameter. Therefore, fine grid near well bore and annulus simulations were conducted to determine temperature, viscosity, pressure profiles along the horizontal well bore. Incremental cumulative oil productions per cumulative energy

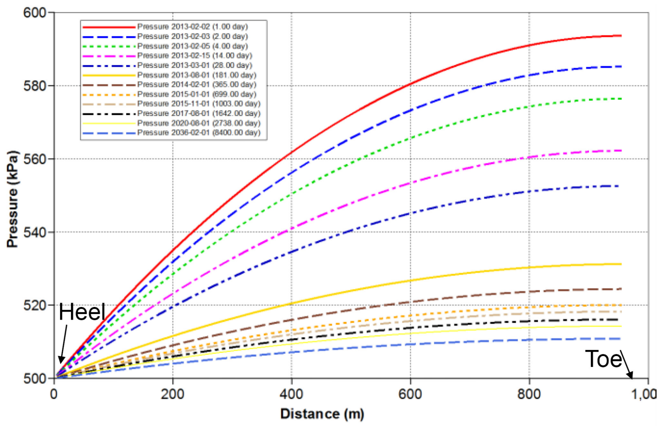

Figure 12—Pressure Draw down in Annulus.

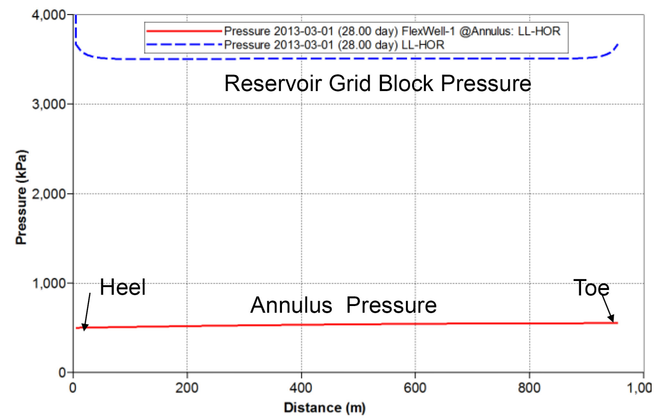

Figure 13—Pressure Draw down in Annulus vs. Reservoir Grid Block (1 m far away from Annulus).

consumptions are analyzed to determine the optimum temperature boundary conditions for given reservoir properties and well bore configurations.

As shown in Fig. 9, horizontal well length is 960 m. Grid sizes are 20 m by 20 m. Net thickness is 20 m and vertical thickness is 1 m. In the near well bore, grid size is less than 1m. Isotropic permeability value of 400 mD is used and Kv/Kh value is 0.3, respectively. The average porosity value is 0.15.

For the base case, well bore temperature was kept as constant like reservoir temperature. After one year cold production, temperature boundary conditions were set to 70 °C, 80 °C, 90 °C, 100 °C, 110 °C, 120 °Cin order to determine the optimum temperature setting for the maximum cumulative oil productions per cumulative energy consumptions.

As shown in Fig. 10, the simulated cold oil production starts with 25 SCM/D, and the cold oil production reaches to 6 SCM/Dafter a year. By setting the temperature to 120 °C, oil rate can be increased from stabilized 6 SCM/D to 12 SCM/D. Similarly, the cumulative oil production can be increased from 29.7 KSCM for the base case to 50.2 KSCM for 120°C case. On the other hand, cumulative energy consumptions are increased almost four times from 17E12 Joule for 70 °C case to 65E12 Joule for 120 °C case. Since, at the end of concession date of 2037, oil rate for base case is 2.5 SCM/D, while the oil rate is only around 4 SCM/D for the 120°C case. Therefore, consuming energy cost for electrical generation and oil prices are another key parameters to determine the optimum temperature settings and operating conditions.

Economics of the project is determined based on incremental cumulative oil production per cumulative energy consumptions, (STB/MMBTU). Required energy rates are determined based on horizontal well length, (Watt/ft). As presented in Table 2, cumulative oil production per cumulative energy consumption is in the order of 3 STB/MMBTU. As the temperature is increasing, cumulative oil production per cumulative energy consumption is decreasing.

As shown in Table 2, the initial energy rate per horizontal well length is around 40–60 Watt/ft. Energy rate per length values required to design power connection compound, power and heating cables. Due to reservoir heterogeneity, distributed temperature profiles with different energy rates can be implemented to maximize production along the horizontal well.

The pressure drops in annulus with 5” casing along horizontal section are also analyzed for different time steps because of the long horizontal well length of 960 m and high viscosity value. As shown in Figs. 12–13, the pressure drop is around 90 kPa at the first day of production. When the pressure at heel is set the 500 kPa as pump pressure, the pressure at the toe is around 590 kPa. There is very low pressure drop of 90 kPa due to low oil rates and casing size of 5”. When the pressure in annulus is compared to nearest reservoir grid block which is 1 m far away from the annulus, the pressure drawdown is around 3000 kPa. At the toe and

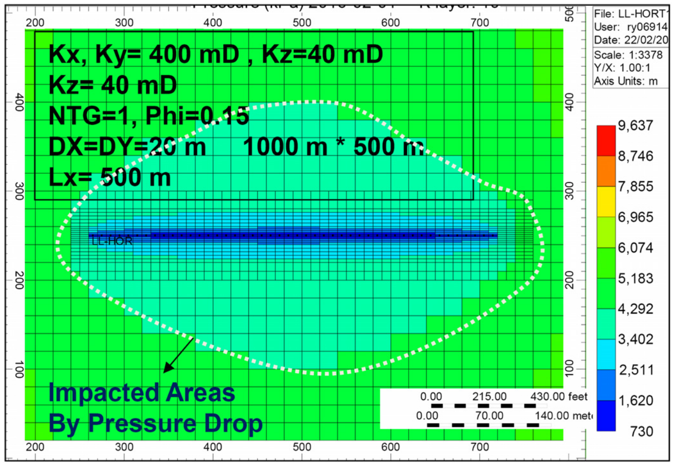

Figure 14—Pressure Distribution after 3 years.

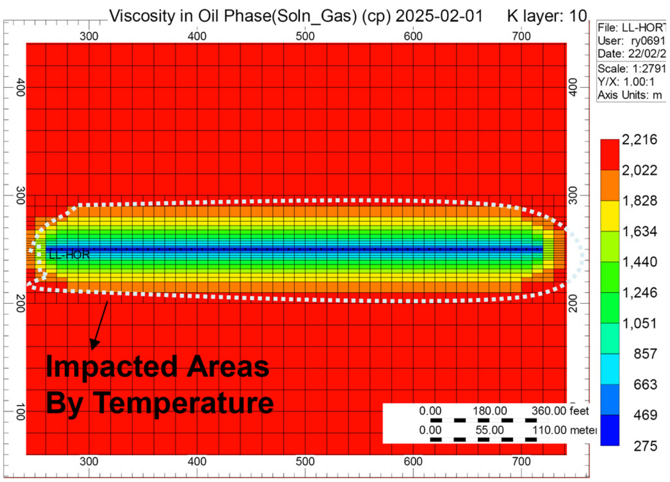

Figure 15—Viscosity Distribution after 3 years.

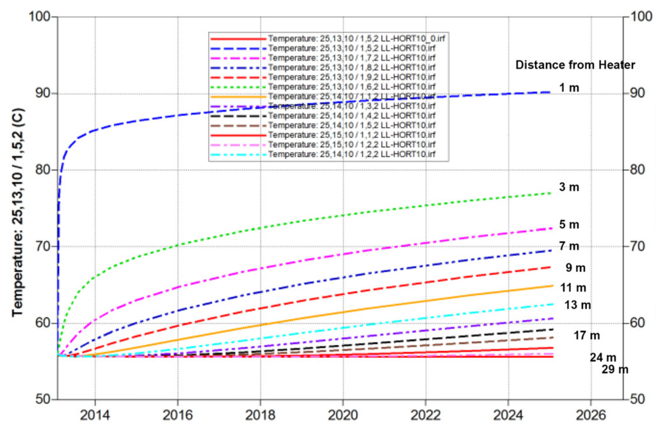

Figure 16—Temperature Profiles.

heel of the horizontal well, drawdown pressure is slightly higher than the central part due to elliptical flow, Fig. 13.

Simulation Model for Olive Zone

Dead oil viscosity for Olive zone is 3880 cp which is much lower than Green zone dead oil viscosity, 11200 cp. However, areal continuity of sands and conglomerates in Olive zone is lower than in Green zone, Fig. 4. In order to explore energy consumptions in a short horizontal well, simulated horizontal length is chosen to be 500 m and Kv/Kh value is chosen to be 0.1. Similarly, the grid sizes are 20 m by 20 m. Net thickness is 20 m and vertical thickness is 1 m. In the near well bore, grid size is less than 1 m. Isotropic permeability value of 400 mD is used. The average porosity value is 0.15. Grid structure and horizontal well configurations are presented in Fig. 14. Measured dead oil viscosities at the highest shear rate for different temperatures are presented in the Fig. 8.

For the base case, well bore temperature was equal to reservoir temperature. After one year cold production, temperature boundary conditions were set to 70 °C, 80 °C, 90 °C, 100 °C, in order to determine the optimum temperature settings. By setting the bottom hole pressure to 500 kPa and initial pressure distribution to 9637 kPa, the pressure distribution along horizontal well after three years of production, Fig. 14.

When the pressure distribution is compared to the live oil viscosity distribution, Fig. 15, it can be seen that drawdown area due to pressure drop, Fig. 14, is larger than the area influenced by well bore

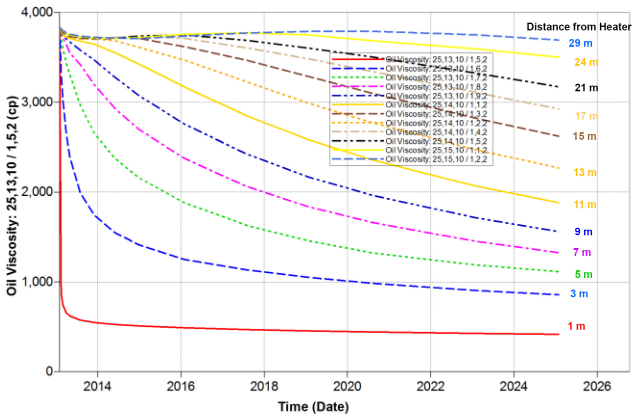

Figure 17—Viscosity Profiles.

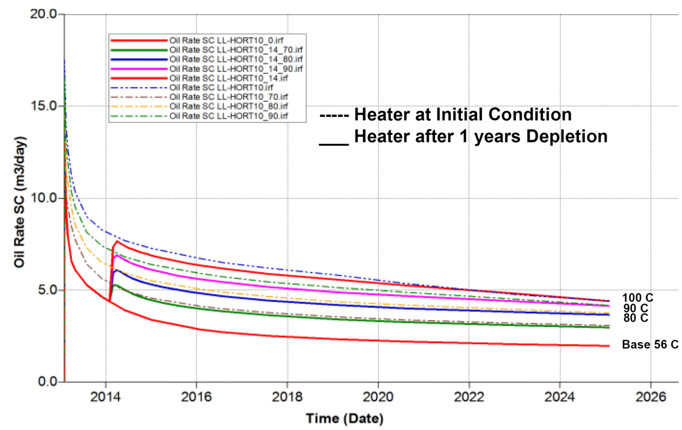

Figure 19—Oil Rates for Different Temperature for Olive.

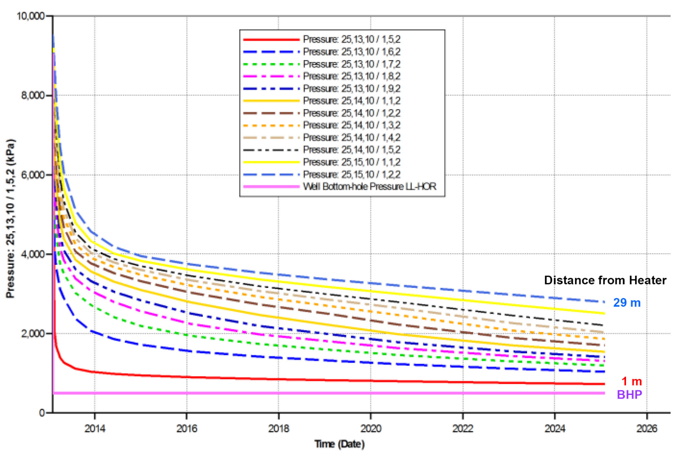

Figure 18—Pressure Profiles.

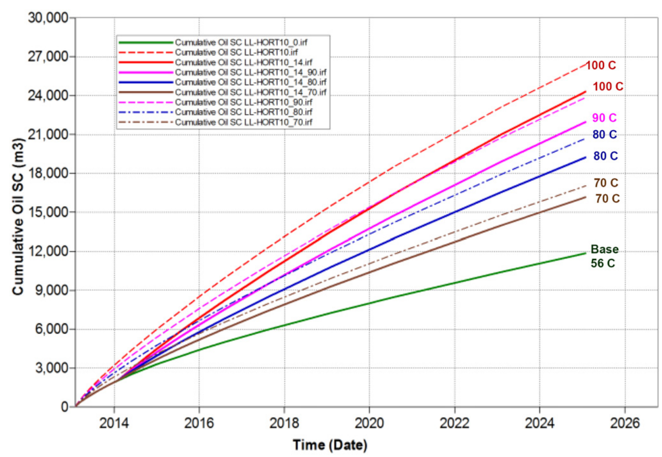

Figure 20—Cumulative Oil Production.

temperature, Fig. 15. Viscous forces due to pressure drawdown in the reservoir are more dominant than heat conduction due to high temperature at the well bore. Well bore heating is acting like negative skin, it is influencing just near wellbore. When the temperature profiles along the horizontal well bore are analyzed, Fig. 16, the maximum distance impacted from heater is 29 m. The temperature is almost similar to the reservoir temperature, 56 °C, after 29 m. When the heater temperature is set to 100 °C, the temperature 1 m far away from the heater can only reach t90 °C after 12 years of heating. Similarly, oil viscosity profiles, Fig. 17 do not show any change after 29 m distance from heater. On the other hand, pressure profiles, Fig. 18, show that pressure drops 29 m far away from the heater is almost 6500 kPa after 12 years of production.

The simulated cold oil production starts with 18 SCM/D, Fig. 19, and reaches a rate of 4.5 SCM/Dafter a year production. Solid lines in Figs. 19–20 are representing the cases in which the heater is implemented after one year of cold production; dot lines are representing cases in which the heater is implanted at the initial condition. In the case of setting the temperature to 100 °C, oil rate can be increased from stabilized 4.5 SCM/D to 7.5 SCM/D. Similarly, the cumulative oil production, Fig. 20, can be increased from 12.87 KSCM for the base case to 24.32 KSCM for the 100 °C case. If the heater is implanted at the initial condition just after completion of the well rather than after one year of cold production, an additional cumulative oil production of 8% can be achieved and heater installation cost also can be reduced.

Cumulative oil production per cumulative energy consumption is in the order of 6 STB/MMBTU as presented in Table 3. When temperature is increasing, cumulative oil production per cumulative energy

Table 3—Incremental Oil Production, Cumulative Energy Cost, and Energy Rate per Length for Olive Zone

TIME	DATE	Np	ΔNp				Cumulative Energy Cost (STB/ MM BTU)				Energy Rate				Energy Rate per Length			
(day)		Base: 56 C	70 C	80 C	90 C	100 C	70 C	80 C	90 C	100 C	70 C	80 C	90 C	100 C	70 C	80 C	90 C	100 C
		SCM	SCM	SCM	SCM	SCM					kWatt	kWatt	kWatt	kWatt	Watt/ft	Watt/ft	Watt/ft	Watt/ft
0	2/1/2013	0																
1	2/2/2013	19																
14	2/15/2013	155																
28	3/1/2013	273																
59	4/1/2013	488																
89	5/1/2013	675																
181	8/1/2013	1185																
303	12/1/2013	1779																
365	2/1/2014	2038																
393	3/1/2014	2155	48	67	88	106	7.24	5.94	5.59	5.16	18	31	44	56	11	19	27	34
424	4/1/2014	2284	81	126	173	214	6.34	5.75	5.58	5.33	15	26	37	47	9	16	22	29
454	5/1/2014	2409	112	181	252	315	6.04	5.76	5.65	5.47	14	24	34	45	9	15	21	27
485	6/1/2014	2539	138	235	329	417	5.75	5.72	5.68	5.55	14	23	33	43	8	14	20	26
515	7/1/2014	2645	179	301	420	530	6.13	6.04	5.95	5.80	13	23	32	42	8	14	20	26
546	8/1/2014	2756	218	366	510	645	6.32	6.22	6.12	5.97	13	22	32	41	8	14	19	25
577	9/1/2014	2866	255	429	598	756	6.41	6.33	6.23	6.08	13	22	31	40	8	13	19	25
607	10/1/2014	2972	288	488	681	862	6.44	6.39	6.31	6.16	13	22	31	40	8	13	19	24
638	11/1/2014	3083	320	546	764	969	6.43	6.43	6.36	6.23	13	21	30	39	8	13	19	24
668	12/1/2014	3189	349	600	843	1072	6.38	6.44	6.39	6.27	12	21	30	39	8	13	18	24
699	1/1/2015	3299	377	655	922	1175	6.32	6.44	6.41	6.30	12	21	30	39	8	13	18	24
789	4/1/2015	3572	495	850	1190	1512	6.71	6.76	6.68	6.55	12	21	29	38	7	13	18	23
911	8/1/2015	3942	637	1098	1532	1948	6.89	6.96	6.86	6.73	12	20	28	37	7	12	17	23
1003	11/1/2015	4221	732	1271	1776	2262	6.89	7.01	6.92	6.79	12	20	28	36	7	12	17	22
1095	2/1/2016	4500	820	1436	2012	2567	6.84	7.02	6.94	6.83	11	19	28	36	7	12	17	22
1277	8/1/2016	5001	1025	1790	2507	3195	7.00	7.17	7.08	6.96	11	19	27	35	7	12	16	21
1642	8/1/2017	5940	1438	2497	3485	4437	7.27	7.41	7.29	7.15	11	18	26	34	7	11	16	20
2191	2/1/2019	7254	2035	3531	4911	6240	7.50	7.63	7.48	7.33	10	17	25	32	6	11	15	19
2738	8/1/2020	8486	2610	4524	6280	7955	7.65	7.76	7.60	7.42	10	17	24	31	6	10	14	19
3652	2/1/2023	10409	3570	6131	8480	10582	7.88	7.94	7.73	7.44	9	16	22	29	6	10	14	18
4383	2/1/2025	11872	4306	7379	10114	12456	8.01	8.04	7.77	7.37	9	15	21	28	5	9	13	17

consumption is not decreasing as much as in Green zone, since the horizontal well length in the Olive zone is almost half-length of Green zone. The initial energy rate per horizontal well length is around 30–35 Watt/ft as shown in Table 3. Short horizontal well is better than long horizontal well in terms of cumulative oil production per cumulative energy consumption. In order to reduce the energy consumption and increase the efficiency, nonproductive intervals along the horizontal well can be avoided by distributed selective heating systems.

Conclusions and Recommendations

- Due to environmental restrictions on surrounding area and deterioration of surface and underground reservoir, downhole electrical heating technique is viable to replace conventional thermal methods for LLancanelo reservoirs.
- In order to reduce the energy consumption and increase the energy efficiency, nonproductive low porosity intervals along the horizontal well can be avoided by distributed selective heating systems.
- The well bore conditions in heterogeneous unconsolidated sandstones and conglomerates with washout environments are crucial to design an effective well bore heating system.
- Well trajectory design in continuously productive intervals without washout environments is the best-desired conditions to implant wellbore heatings.

- If the heater is implemented at the initial condition rather than after one year of cold production, an additional cumulative oil production of 8% can be achieved and heater installation cost also can be reduced.
- It has been shown that electrical well bore heating was economically viable in environmentally sensitive and heterogeneous reservoirs.
- An additional oil recovery for Olive zone can be increased up to 110% while an additional oil recovery for Green zone can reach up to 62%.
- Energy consumption of 1 MM BTU for Olive zone will lead an additional oil recovery of 6 STB, whereas 1 MMBTU consumption for Green zone will lead an additional oil recovery of 3 STB.
- Energy rate per horizontal length is in the range of 40–60 Watt/ft per the Green zone.
- Well bore heating will not change the reservoir temperature and viscosity of the oil beyond 30 m far away from heater.

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