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Electromagnetic Heating Methods for Heavy Oil Reservoirs

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Abstract

The most widely used method of thermal oil recovery is by injecting steam into the reservoir. A well-designed steam injection project is very efficient in recovering oil, however its applicability is limited in many situations. Simulation studies and field experience has shown that for low injectivity reservoirs, small thickness of the oil-bearing zone, and reservoir heterogeneity limits the performance of steam injection. This paper discusses alternative methods of transferring heat to heavy oil reservoirs, based on electromagnetic energy. We present a detailed analysis of low frequency electric resistive (ohmic) heating and higher frequency electromagnetic heating (radio and microwave frequency).

We show the applicability of electromagnetic heating in two example reservoirs. The first reservoir model has thin sand zones separated by impermeable shale layers, and very viscous oil. We model preheating the reservoir with low frequency current using two horizontal electrodes, before injecting steam. The second reservoir model has very low permeability and moderately viscous oil. In this case we use a high frequency microwave antenna located near the producing well as the heat source. Simulation results presented in this paper show that in some cases, electromagnetic heating may be a good alternative to steam injection or maybe used in combination with steam to improve heavy oil production. We identify the parameters which are critical in electromagnetic heating. We also discuss past field applications of electromagnetic heating including technical challenges and limitations.

Introduction

While steam injection may be an effective method for improving heavy oil production, there are certain situations where it may not work very well. These could be for:

1. Very deep formations, where heat losses in the wellbore are significant and the quality of steam reaching the formation is very low.
2. Thin pay-zones, where heat losses to adjacent (non oil-bearing) formations may be significant.
3. Low permeability formations, where the injected fluid may have difficulty penetrating deep into the reservoir.
4. Reservoir heterogeneity, where high permeability streaks or fractures may cause early injected fluid breakthrough and reduce sweep.
5. Situations where generating and injecting steam may be environmentally unacceptable (example: through permafrost) or commercially uneconomical (in space limited offshore platforms).

In this paper we discuss alternative methods for heating heavy oil reservoirs, which may be economically viable alternatives to steam in certain situations. We describe two electromagnetic heating methods – low frequency electric resistive (ohmic) heating and high frequency microwave heating. We demonstrate the applicability of electromagenetic heating with two example reservoirs – one which has a thin sand zones separated by impermeable shale layers and another which has moderately viscous oil and low permeability.

For tar-sands or extremely high viscosity reservoirs, where the temperature effect on viscosity is significant, electromagnetic heating could be used as a pre-heating tool to create preferential pathways for steam injection. This would minimize the heat losses[1] during steam injection, and improve steam injection performance.

Past studies[2-34] have shown some promise in the process, however there are few field applications of electromagnetic heating or comprehensive modeling efforts. Compared to other thermal IOR methods, electromagnetic heating still remains a peripheral technology, even though it the potential was recognized more than three decades ago.

Electromagnetic Methods for Heating Oil Reservoirs

Electrical heating of a formation can occur in a number of ways, depending on the frequency of the electrical current. In the high frequency range (radio frequency and microwave), dielectric heating prevails, and the dipoles formed by the molecules tend to align themselves with the electric field. The alternation of this field induces a rotational movement on the dipoles, with a velocity proportional to the frequency of alternation. The molecular movement may result in significant heating, as is seen in microwave ovens. When low frequency Alternating Current is used, it is the resistive or ohmic (I^2R) heating which is dominant. A third method of electrical heating is inductive heating, where Alternating Current flowing through a set of conductors induces a magnetic field in the surrounding medium. The variation of the magnetic field, in turn, induces secondary currents, whose circulation in the medium generates heat.

In this paper we discuss and model low frequency electric resistive heating and high frequency microwave heating.

Low Frequency Electrical Resisitive Heating

Electrical resistive heating or ohmic heating may occur when low frequency alternating current flows through the reservoir, and electrical energy is converted into heat. In the simplest configuration (Figure 6), two neighboring producing oil wells may act as cathode and anode. A potential difference is applied across the two electrodes and an electrical path through the formation is provided by the formation (in-situ) water. As such, to maintain the electrical circuit, the formation temperatures should be kept below the boiling point of water (at the formation pressure).

A detailed review of the Ohmic Heating simulator used in this study is presented in References [28] and [29]. We present only a few key concepts in this paper.

Conservation of electric charge requires that:

$$?J = Q \tag{1}$$

where J = current density

Q = electric charge injected or extracted at a location per unit time
∇ = gradient operator.

It is assumed that the time derivative of the volumetric charge density is negligible since the time dependent variation of the driving electric field is slow enough for capacitive effects to be neglected.

Also, from Ohm's Law

$$J = -\sigma \quad \Phi \tag{2}$$

where Φ = electric potential
σ = electrical conductivity

Waxman-Smits model [34] is used to capture the dependence of conductivity on temperature, saturation and lithology.

$$\sigma(T, S_W) = \phi S_W \quad \frac{\phi S_W}{\rho_{ionic}(T)} + B(T)Q_{vb} \tag{3}$$

where
ρ_{ionic} = water resisitivity
B = exchange cations equivalent conductance

Q_{vb} = bulk cation exchange capacity
= $265[1-\phi]$ equiv/m^3 for sands
= $504[1-\phi]$ equiv/m^3 for shales

From Equation 3, it is evident that presence of water is a necessary criteria for low frequency ohmic heating, as with decreasing water saturations the conductivity decreases. The coupling of electrical heating with a regular finite-difference flow simulator (through the source term in the heat equation and also through the temperature and saturation dependence on electrical conductivity) is described in Reference [28].

Features of the Simulation Model

1. The simulation model is a Cartesian, three-dimensional model with 24 x 24 x 18 grid blocks of $\Delta x = \Delta y = 14.32$ ft and Δz is variable, with finer gridding near the horizontal wells (and electrodes).

2. The middle sand is 30 feet thick, whereas the top and bottom sands are 10 feet in thickness. The three sands are separated by two impermeable shale layers of 5 feet thickness.

3. Heavy oil has been represented as a single-component oil of 14.1°API and molecular weight of 400.

4. Heavy oil viscosity at the initial temperature of 95°F is 9541 cp. Viscosity – Temperature relationship is given in Table 1.

1. The sands in the reservoir model have $k_x = k_y = 2{,}500$ md, $k_z/k_x = 0.5$, $\phi = 0.36$, Initial reservoir temperature = 95

°F, initial oil saturation = 0.5, initial water saturation = 0.5. The shales have water saturation = 1.0. Initial reservoir pressure = 360 psia at the formation top depth of 800 ft. The reservoir has a 10 degree dip.

6. Two horizontal electrodes are placed at X = 1 and X = 24, in the middle sand (Z = 9). It is assumed that the horizontal wells serve as the electrodes. The preheating runs were performed at 300V, 2-phase AC at 60Hz.

7. Constant steam injection rate of 200 Bbls/Day of CWE at Steam Quality = 0.7 is maintained throughout the simulation period. Coordinates of the injector are X=13, Y=16.

8. Producers operates under a constant flowing bottomhole pressure constraint of 14.7 psia.

9. Injector is completed in layers 4 through 9 (bottom three layers) whereas the horizontal producers in Layer 9 (X=1 and X=24) are completed throughout.

10. Relative permeability curves are specified using power-law type relations with $S_{wc} = 0.45$, $S_{org} = 0.12$, $S_{orw} = 0.23$ $S_{gc} = 0.0$, $k_{rocw} = 0.8$, $k_{rwro} = 0.12$, $k_{rgro} = 0.45$, $N_w = N_{og} = = N_{ow} = N_g = 2$.

Stone II method is used to compute three-phase relative permeability using two-phase relative permeability data.

Analysis of Electric Resistive (Ohmic) Heating Simulations

We simulated low frequency electric resistive heating for a period of 6 months. At the end of 6 months the temperature distribution in layer 9 (containing the horizontal electrodes) is shown in Figure 3. Ohmic Heating is a near well-bore effect, with temperatures reaching 400°F near the two electrodes. At a distance of 100 feet from the well, the temperature after 6 month of pre-heating is about 170°F (or 75°F over the initial reservoir temperature of 95°F).

After 6 months of preheating, steam is injected from the central injector, located at X=13, Y=16. The temperature distribution after 2 months and 1 year of steam injection following electric pre-heating is shown in Figures 4 and 5 respectively. In comparison, the temperature distribution after 1 year of steam injection in a cold reservoir is shown in Figure 6. It is evident from the simulation results that electric pre-heating allows for a more-uniform and widespread heating of the reservoir. This translates into accelerated production at the beginning and higher cumulative oil during the duration of the simulation. The length of the electrodes, power requirements and time for preheating can be optimized for specific projects. We do not present any optimizations in this paper.

An important consideration in Ohmic Heating simulations is to appropriately handle the effect of water saturation on heating. As the temperature rises in the reservoir, and boiling occurs, the resistivity increases (following Waxman and Smits [34] model presented in Equation 3). This reduces the current and heating decreases (as it is proportional to I^2). Keeping the temperature below the boiling point of water at reservoir pressure helps in the broader distribution of electric heat.

The presence of shales, having Sw = 1.0, also has a significant effect on heating. Figure 7 shows the temperature distribution across the X-Z cross-section of the simulation model when shales are present. In comparison to Figure 8 (when shales are absent), the heated zone in Figure 7, is stretched out or elongated. This happens because the higher conducting shales conduct current further into the reservoir, increasing the heated region. The location of the electrodes with reference to the water-bearing shales can be optimized for best over-all heating.

High Frequency Electromagnetic Heating

From Maxwell's equations the following simplied expression for average power dissipated in a volume *V* can be derived:

$$P_{ave} = \omega \varepsilon_o \varepsilon'' E^2 V \qquad \text{watts}$$

or

$$\bar{p} = \sigma E^2 \quad \text{watts per cubic meter}$$

where

conductivity $\sigma = \omega \varepsilon_o \varepsilon''$

and

ω = radian frequency
ε_o = free space dielectric constant
ε'' = loss factor (proportional to the electromagnetic energy absorbed by the porous media)
E = rms electric field intensity in volts per meter.

As electromagnetic energy is absorbed by the porous media, the increase in temperature can be calculated from the following simple equation:

$$\sigma E^2 dt = \rho c_p dT$$

where

ρ = mass density in kg/m^3
c_p = specific heat at constant pressure

$$\frac{dT}{dt} = \frac{\sigma E^2}{\rho c_p}$$

For an imposed electric field E, the rate of temperature increase depends on $\dfrac{\sigma}{\rho c_p}$

The dielectric constant varies with frequency and temperature, an can be measured in the laboratory.

Microwave Heating

The penetration depth of microwaves is usually small, but for relatively mobile reservoir fluids the microwave energy continuously heats fluids as they are drawn towards the producing well. The microwave antenna can be placed in a drilled hole close to the producing well. A schematic of the microwave heating process is shown in Figure 10. Drilling and completion considerations are discussed in Reference [13].

The microwave energy distribution may be obtained from an analytical solution[14] to the antenna equation. The solution presented here represents the solution for a single point source, and the complete antenna consists of a linear array of these point sources [35]. The energy absorbed by the grid block i (per unit volume per unit of time) due to the k'th point source, P_i^k is calculated according to the coordinates of the grid block and its relation to the source.

For a block i containing a point source,

$$P_i^k = \frac{2P_o^k\alpha^2}{V}\left[\frac{1}{(2\alpha^2)} - \left(r^2 + \frac{r}{\alpha} + \frac{1}{2\alpha^2}\right)e^{-2\alpha r}\right]$$

where

α = attenuation of block i

r = equivalent radius for block i (radius of a sphere having the same volume as block i)

P_i^k = energy absorbed by block i due to the k'th point source (which is block i)

P_o^k = antenna power for the k'th point source in the linear array

V = volume of block i

A 3-D, 3 Phase (oil, water and gas) finite difference simulator TERASIM [35] was used to study the process of microwave heating. A 17*17*34 grid block model was created to simulate a 2.5 acre region, which is about 900 feet in thickness. The reservoir permeability and initial oil saturation through a cross section in the middle are shown in Figure 11. We set the microwave antenna (frequency = 0.915 GHz) in the lower part of the formation (Figure 12) at a distance of about 30 feet from the producing well. Heating the lower layers of the formation has a distinctive advantage because of a combination of factors; higher pressures, the reservoir model has better initial oil saturation in the lower layers (as seen in Figure 11) and that gravity drainage aids in improving recovery.

Features of Simulation Model

1. The simulation model is a Cartesian, three-dimensional model with 17 x 17 x 34 grid blocks of Δx = 19.41 ft , Δy = 22.85 ft. The producer is fractured and fracture half-width = 400 ft. Δz is variable, and the layers containing the microwave source have Δz = 30 ft.

2. Oil viscosity at the initial temperature of 100°F is 33.11 cp. Viscosity – Temperature Relationship is shown in Table 2.

3. The model represents a heterogeneous layered reservoir with very low permeability. Figure 8 shows a cross-section of the permeability field through the center of the model. ϕ = 0.47. Initial oil saturation is given in Figure 9.

4. Initial reservoir pressure for simulation = 194 psia at the formation top depth of 806 ft. In the lower layers where the microwave antenna is located, the initial pressure is around 1300 psia.

5. The microwave antenna is assumed to be 30 ft in length and placed at a distance of 30 ft from the producing well.

6. The frequency of the microwave source is 0.915 GHz. The power and number of sources was varied – the results presented in this paper are for:
   a) Case:1 30 kW source in Layer 30
   b) Case:2 45 kW source in Layer 30
   c) Case:3 60 kW source in Layer 30
   d) Case:6 60 kW source in Layer 30 and a second 60 kW source in Layer 25.

7. Producer operates under a constant flowing bottomhole pressure constraint of 90 psia.

Analysis of Microwave Heating Simulations

Simulations conducted using the TERASIM [35] microwave simulator show that temperature near the microwave source increases to around 400°F(or 300°F over the initial reservoir temperature of 100° F). After 5 years of heating, the temperature at a distance of 60 feet from the source is around 200° F. Temperature maps are shown in Figures 12 and 13, whereas Figure 14 plots the radial distribution of temperature from a 60 kW microwave source. Figure 15 compares the cumulative oil production for microwave heating scenarios with primary production. When two 60 kW sources are placed (Case 6) in Layers 25 and 30 respectively, there is an 80% improvement in cumulative oil recovered over primary production in 10 years. The power requirements after 10 years of heating were estimated to be around 200-250 kW-hr/Incremental Bbl of Oil produced for the various cases discussed.

Some Field Applications of Electromagnetic Heating

Pizarro and Trevisan[8] presented data from a low frequency electrical heating field test at the Rio Panan field in Brazil. Production increased from 1.2 Bbls/day to 10 Bbls/day after 70 days of applying an average power of 30kW across neighboring producing wells (328 feet apart) in a reservoir with rather viscous oil (2500 cp at reservoir conditions).

Kasevich *et al*. [16] performed a laboratory study of RF heating, in which low permeability diatomite samples filled in a 55 gallon drum were heated with an electric monopole. After 49 minutes of heating with a 400 watts and 50.55 MHz source, the temperature rose by 125C. Subsequently a field test was carried out at the North Midway field [16]. The test well was located where the diatomite interval was relatively homogeneous, starting at 500 feet. A mobile RF heating system was assembled around a 25 kW, 13.56 MHz generator. The RF applicator was 25 length and placed at a depth of 620 feet, enclosed in a 250 feet RF transparent glass/epoxy composite liner. Borehole temperature measured at 605 feet depth, rose to approximately 220°F (approximately 130F above formation temperature of 90°F) after 40 hours of RF heating.

Radio frequency field tests carried out in the oil shales of Utah[13] showed a good heating potential. A RF power source – a 40 kW radio transmitter was used at a frequency of 13.56 MHz. The RF power levels were kept in the range of 5 kW to 20 kW and temperatures were recorded in the range of 340°C – 400°C. Two radio frequency field tests in tar sands of Utah[13] were carried out in 1981. RF power input to the tar sand test volume varied between 40 and 75 kW and average temperatures of about 120°C – 200°C were achieved for the two experiments.

Davison[24] presented field test results of electromagnetic stimulation of Llyodminster Heavy Oil Reservoir (~11.4 API). Though production response to electrical heating was observed, casing insulation failure led to early termination of the test.

Summary and Conclusions

We modeled pre-heating a reservoir with thin sands separated by shale layers with two horizontal electrodes, operating at 300V and 60 Hz (2 Phase AC). Low frequency Ohmic Heating is a near well-bore effect, with temperatures increasing by 300°F near the two electrodes for the example reservoir. At a distance of 100 feet from the well, the temperature increase after 6 month of pre-heating is about 75°F. Following steam injection after pre-heating provides a uniform distribution of heat in the reservoir. Simulations show that electrical pre-heating significantly accelerated early production and resulted in better cumulative oil production compared to the non pre-heated case for the duration of the simulations.

We also performed simulations which show that high frequency microwave heating may be used for stimulating oil production in moderately viscous, low permeability reservoirs. The microwave source could be located in a well close to the producer (~ 30 feet) and operate at a frequency close to 1 GHz. Simulations show that a 60 kW microwave source, could increase formation temperatures by 300°F near the source within a year of heating. This results in an 80% increase in cumulative oil production over primary production when 2 60 kW microwave sources are placed in the formation over a period of 10 years.

The different variations of electromagnetic heating: microwave frequency, radio frequency and ohmic heating, may be applied, depending on reservoir and fluid properties. Electrical conductivity increases with increasing water saturation, and for oil sands may be proportional to approximately the square of the saturation. Low frequency (~ 60 Hz) electric resistive heating could be achieved by applying a potential difference across two electrodes attached to two producing wells in the formation. The electric circuit is completed through the formation, with the in-situ water providing the conductivity. However, electric resistive or ohmic heating is reduced where there is little water content or if the water is heated above its boiling point to form steam. In such cases, higher frequency electromagnetic waves can propagate for much larger distances, and heat regions relatively far from the electrode. A region devoid of water near a severely overheated electrode, presents a very large resistance at 50-60 Hz while it is easily permits propagation of a high frequency electromagnetic wave.

Another major consideration in Electromagnetic Heating is wellbore power transmission and associated power losses. In addition to heating the formation, the electric current produces heat in the wellbore delivery system. To improve the efficiency of Electromagnetic Heating, it is necessary to keep the power dissipated in the wellbore delivery system to a small fraction of the power dissipated in the formation.

Stroemich *et al*. [26] have shown that for many common wellbore casings, current levels as low as 100 A rms cause non-linear magnetization of the wellbore steel. This, in turn causes hyestersis power losses in the casing and leads to impedances that are much greater than those observed at low current levels. A good understanding of the electrical properties of insulating materials and their degradation under temperature, pressure and fluids must be known so that current leakage through the electrical insulation may be assessed and maximum allowable wellbore and electrode temperatures may be set. Such precautions would help in minimizing the risks of electromagnetic heating field tests.

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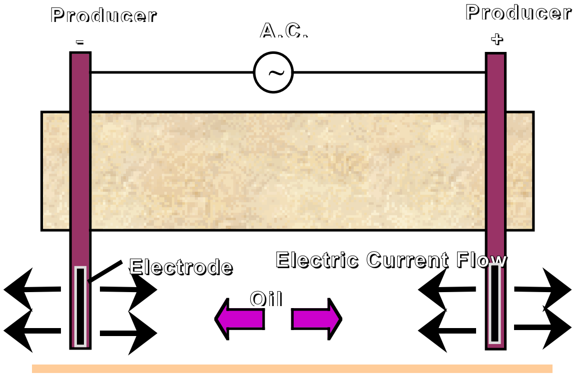

Figure 1. Schematic of Electric Resistive Heating

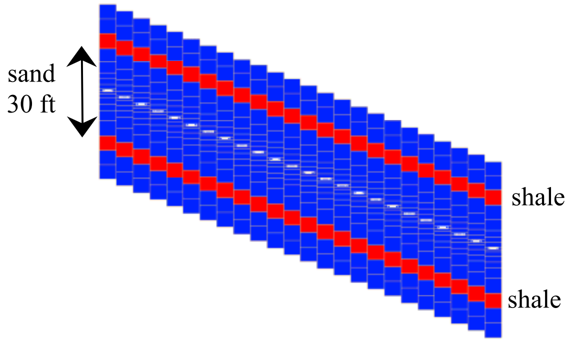

Figure 2. Cross-Section Schematic of Reservoir Modeled for Low Frequency Electric Heating (Example 1).

Table 1. Oil Viscosity-Temperature for Example 1.

Temperature (F)	Oil Viscosity (cp)
95	9541.0
100	6543.0
120	2230.1
140	866.4
160	410.9
180	213.4
200	122.4
210	90.0
220	74.8
240	47.3
280	23.0
340	9.6
380	7.0
400	5.2
500	3.0
600	1.4
800	1.0
1000	0.5

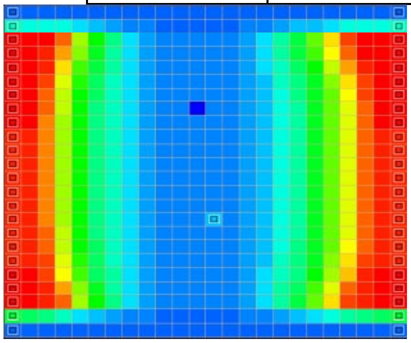

Figure 3. Temperature at 6 months of Preheating (in Layer 9)

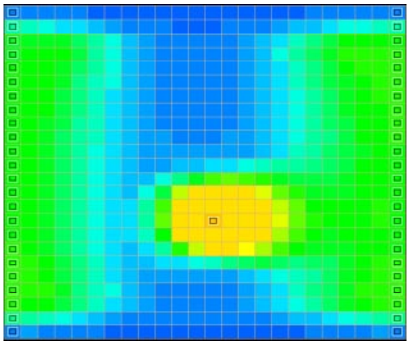

Figure 4. Temperature after 2 months of Steam Injection after 6 months of pre-heating (in Layer 9)

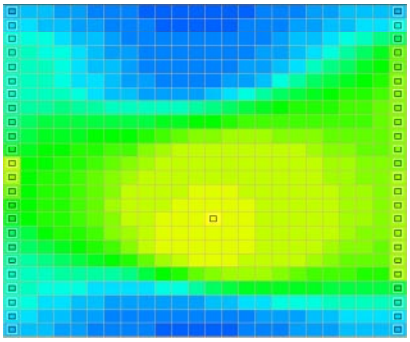

Figure 5. Temperature after 1 year of Steam Injection after 6 months of pre-heating (in Layer 9)

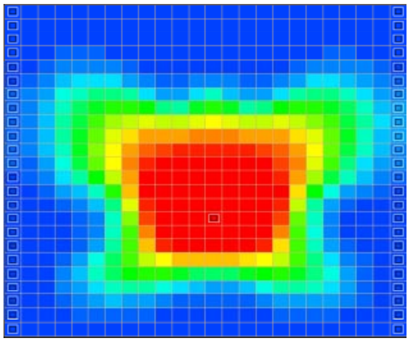

Figure 6. Temperature after 1 year of Steam Injection in a

cold reservoir.

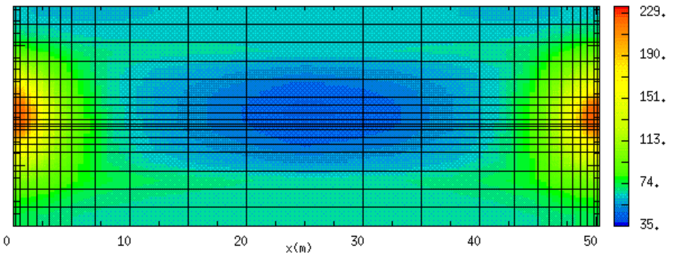

Figure 7. X-Z cross-section of Example 1 showing temperature distribution after 12 months of electric heating.

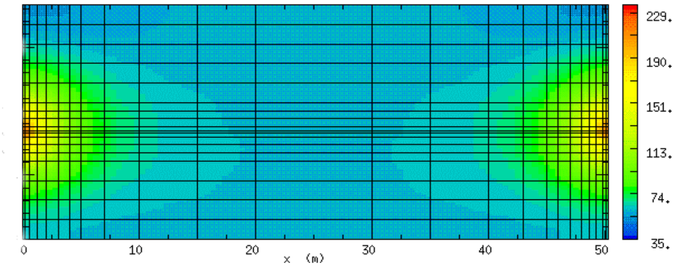

Figure 8. X-Z cross-section of Example 1 (without the shales) showing temperature distribution after 12 months of electric heating.

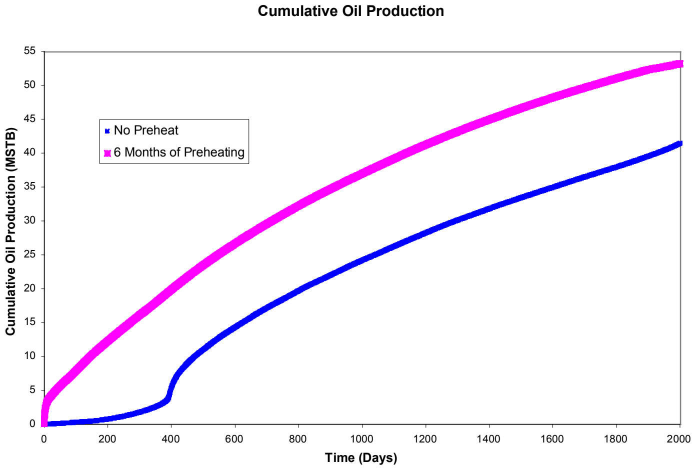

Figure 9. Cumulative Oil Production from Horizontal Wells with and without Preheating

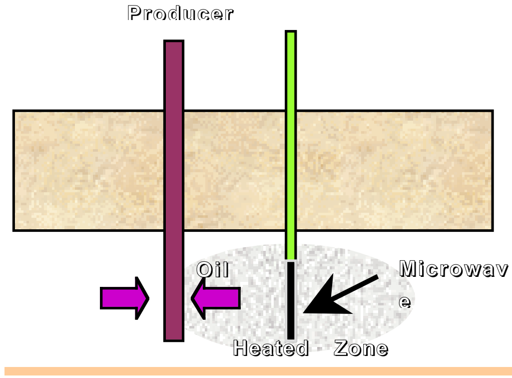

Figure 10. Schematic of Microwave Heating

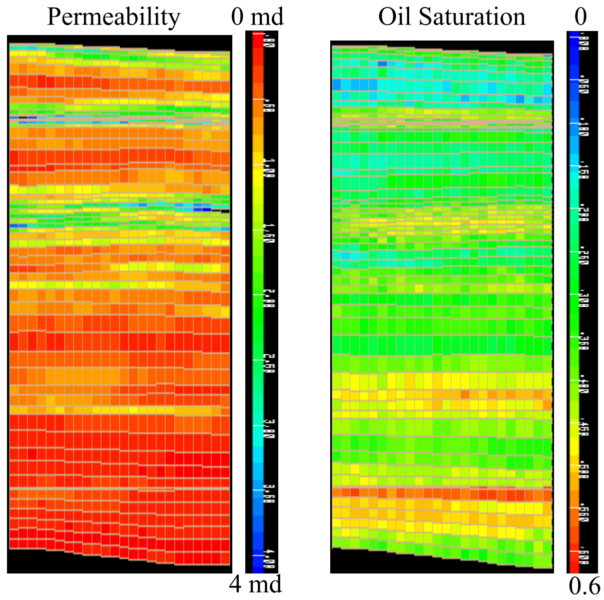

Figure 11. Permeability and Oil Saturation for Example 2.

Table 2. Oil Viscosity-Temperature for Example 2.

Temperature (F)	Oil Viscosity (cp)
100	33.11
111	15.86
150	6.031
200	2.057
250	1.002
300	0.607
350	0.427
400	0.330
450	0.270

500	0.235
550	0.209
600	0.193

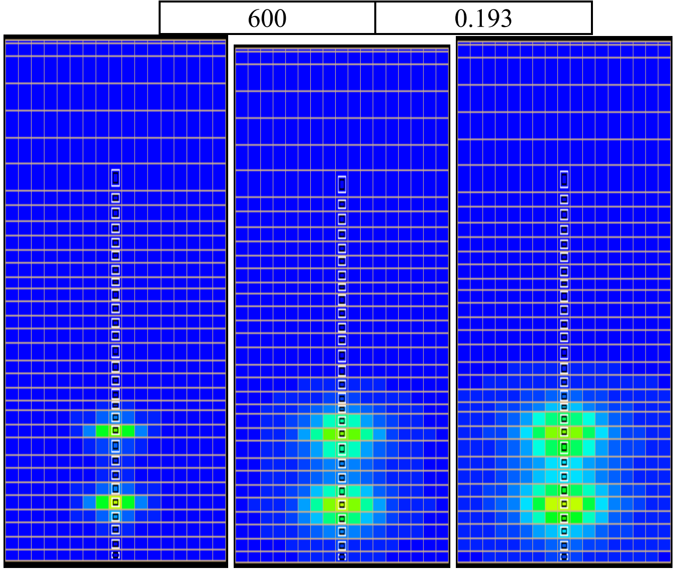
Time = 1Year Time 5 Years Time = 10 Years

Figure 12. Temperature Distribution for Case 6: 60 kW microwave source in Layer 30 and another 60 kW microwave source in Layer 25.

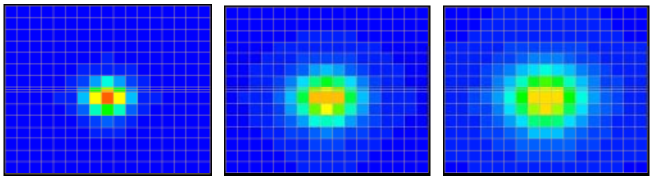
Time = 1Year Time 5 Years Time = 10 Years

Figure 13. Temperature Distribution for Case 6 (Layer 30).

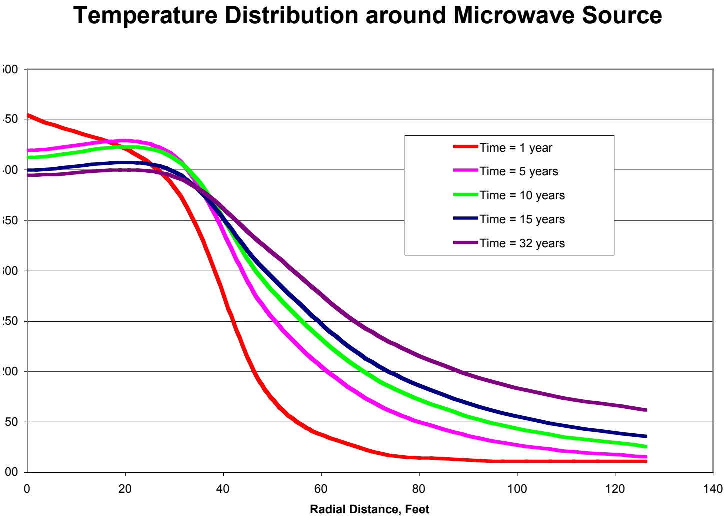

Figure 14. Temperature Distribution around Microwave Soruce (Case 6).

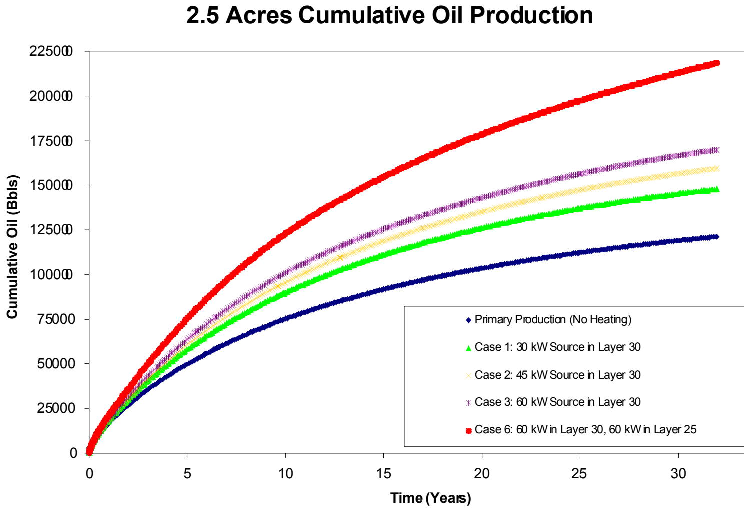

Figure 15. Cumulative Oil Production for Various Scenarios for Example 2. A Base Case with primary production is also provided.