In Situ Electromagnetic Heating for Hydrocarbon Recovery and Environmental Remediation

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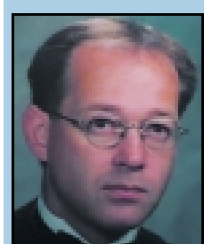

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Introduction

Thermal recovery methods, as applied in heavy oil and oil sand deposits, and in environmental remediation, have the common objective of accelerating the hydrocarbon recovery process. Raising the temperature of the host formation reduces the oil and bitumen viscosity, and, in environmental remediation, increases vapour pressure. These effects assist in sweeping the substances to be recovered from the formation when driving agents are externally injected or when autogenous processes come into play.

Transferring electromagnetic energy to the deposit is proving to be an effective means of supplying the necessary heat. In this electro-thermal process electromagnetic energy is converted to heat in situ using a system of wellbore electrodes from which currents flow through the formation. By proper choice of electrode location and spacing, considerable control can be exerted over the path taken by the currents and, hence, over the temperature profiles that will develop in the formation. Electro-thermal processes are mostly free of problems related to very low initial formation injectivity, poor heat transfer, and the difficulty of controlling the movement of injected fluids and gases, which have plagued other thermally stimulated recovery processes.

Most electro-thermal processes are carried out at power frequencies where the formation acts as a resistive heating element between the various electrodes. At this low frequency, current flow in the formation is primarily via ionic conduction through the water-saturated portion of the interconnected pore spaces in the reservoir. Due to the inherent geometry of current flow emanating from an electrode, current densities and heating rates are highest near the electrodes. Care must be taken lest the water in the immediate vicinity of the electrodes vapourizes and the continuous water path between electrodes is broken. Hence, power frequency heating is generally appropriate when the desired temperatures to be achieved in the formation are lower than the in situ steam temperature.

A variation of power frequency heating, termed inductive heating, is achieved by placing the primary winding of a current transformer inside the casing at the bottom of the wellbore. The section of casing adjacent to the transformer acts as a single turn secondary winding. Large induced currents resistively heat the steel of the casing, and heat is transferred to the formation by thermal conduction. By increasing the frequency to multiples of the power frequency, the rate of heating can be proportionately increased. At greater frequencies however, the electrical transmission losses and capital cost of equipment will also increase.

In a further variation of power frequency heating, the casing, or a section thereof, is resistively heated by the flow of large currents in the casing itself. The adjacent formation is heated by thermal conduction from the casing. This approach shows promise in the heating of long horizontal wells, with applications, for instance, in processes related to steam assisted gravity drainage or in surface mining of tar sands.

All formation heating at power frequency has the inherent advantage of the ready availability of 60 Hz power and the associated apparatus, such as transformers and measurement equipment. Since heating at power frequency is a viable approach to formation heating, a need to consider in situ electromagnetic heating at frequencies much higher than 60 Hz is not immediately evident. As the moisture content of the formation is decreased, however, whether this is due to little water content in the formation to begin with, or because water has been driven off by heating above the steam point, higher frequencies become necessary.

The rate, in W/m^3, at which electrical energy is converted to heat within unit volume of formation, is given by σE^2. Here, σ is the effective electrical conductivity in S/m, and E is the rms electric field intensity in V/m. The effective electrical conductivity increases as the square of the water content by weight. It is made

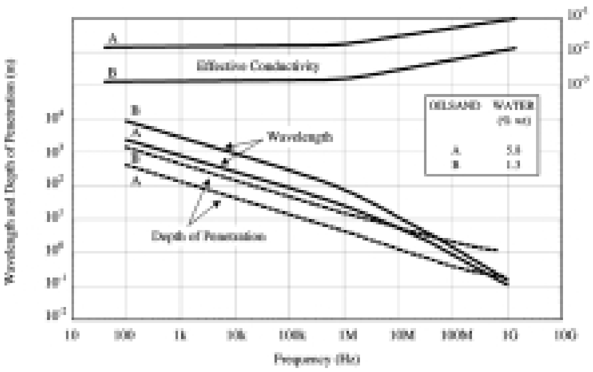

FIGURE 1: Effective conductivity, wavelength and depth of penetration as a function of frequency.

up of two terms, where each term is the manifestation of a distinct physical process. The first term is due to the aforementioned ionic conduction, from which heating is derived by the transfer of kinetic energy to the bulk of the pore water from the *free* charge carriers that have been accelerated by the applied electric field. This term, which is independent of frequency, dominates at frequencies below about 10^6 Hz. At frequencies above 10^7 Hz the situation changes. The second term dominates and the pore water and all other constituents of the formation are heated directly at the atomic or molecular level by the transfer of kinetic energy from *bound* charges oscillating in the applied electric field. This second term is directly proportional to the number of oscillations per unit time, and, therefore, increases linearly with frequency. The dependence of effective electrical conductivity on water content and frequency is illustrated in Figure 1, which shows averaged data obtained from many measurements on reconstituted samples of typical Athabasca oil sands[1]. It follows from the foregoing that use of higher frequencies allows heating of those formations that have low electrical conductivities at 60 Hz, without the need for excessively large electric field intensities.

While formation heating at high frequency is technically feasible, there are several factors that must be considered. These include the relatively high cost of the capital equipment required to convert 60 Hz power to high frequency, electrical losses in the frequency conversion, and the need to match the electrical impedance of the formation to the output impedance of the source. Also, as frequency is increased, there is a decrease in wavelength and the distance to which electromagnetic energy penetrates the formation, which may lead to non-uniform formation heating. This, generally, is undesirable. The behaviour of these two parameters as a function of frequency is shown in Figure 1 for two typical oil sand formations having different moisture contents. It is seen that the depth of penetration is reduced to the order of 20 cm in oil sand "A" as the microwave region is approached at 10^9 Hz. Hence, while microwave heating finds wide applications in other areas, such as the cooking of popcorn, it is unsuitable or severely limited for in situ heating applications.

Electrical Stimulation of Heavy Oil Wells

Numerous field tests of electrical heating have been reported in

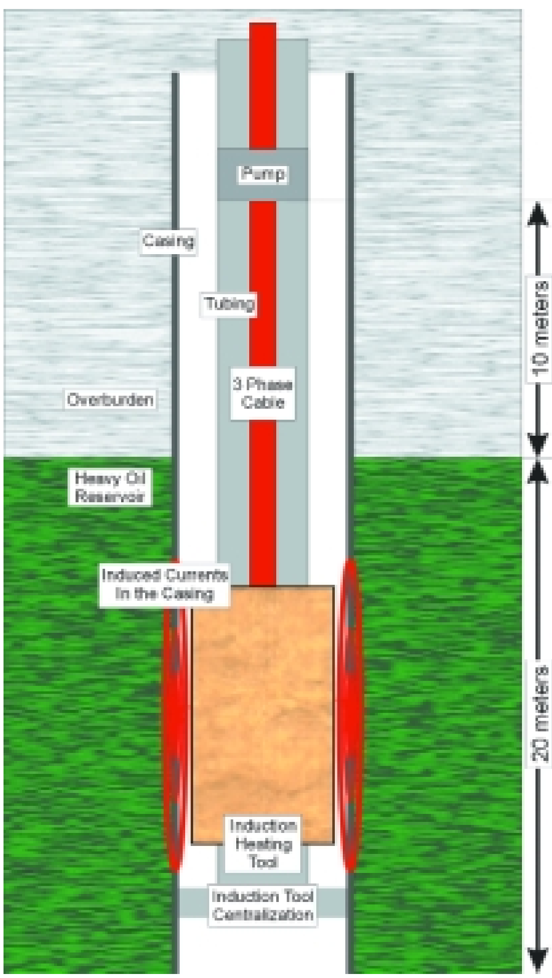

FIGURE 2: Wellbore configuration for the *Inductive* method.

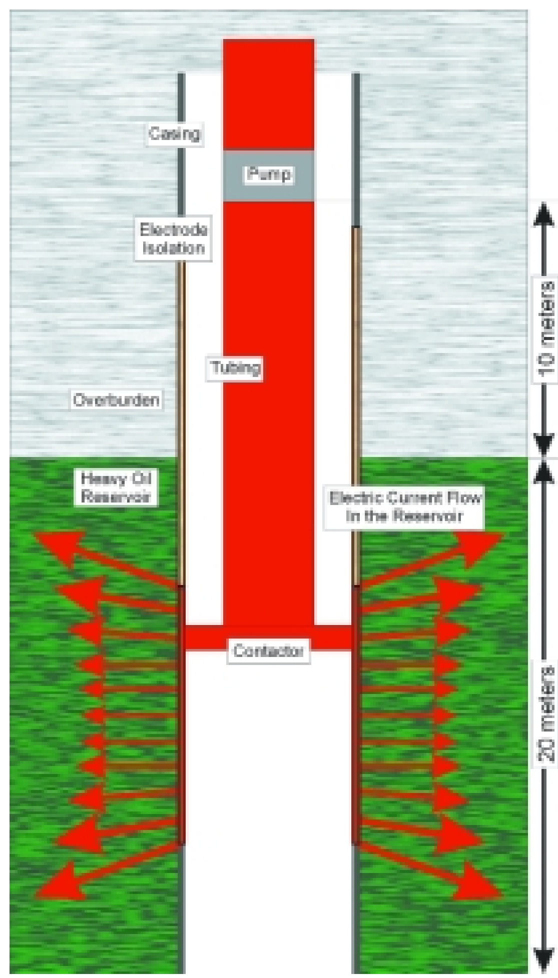

FIGURE 3: Wellbore configuration for the *Resistive* method.

TABLE 1

Feature	Inductive Method	Resistive Method
Completion	Retrofit an existing wellbore with induction tool.	Requires new wellbore with an electrode design.
Source of Electrical Heating	Induced currents in the casing.	Resistive heating (I^2R losses) in the reservoir.
Heated Radius	Less than 2 m	5 to 10 m
Power Requirements	10 to 40 kW	20 to 80 kW
Maximum Temperature	140 to 160˚ C	120 to 180˚ C
Power Delivery System	3-phase, low current, high voltage.	Single phase, high current, low voltage.
Flexibility	Can be moved in the wellbore. Used in both vertical and horizontal wells.	Permanent location. Typically limit ed to vertical wells.

the literature[2-6]. The results are consistent: *significant stimulated production rates were attained, but long-term heating could not be achieved due to shortcomings in operational strategies and failures in the oil production system*. However, the engineering design for wellbore stimulation has evolved considerably and the technology may soon be commercially viable. The purpose of this section is to present two different methods of electrical stimulation, at power frequency, that show particular commercial promise. Each method is discussed making reference only to the physics of the process. We present the differences between these methods in terms of the production and thermal response. Also, the economics of the two methods are calculated and compared to that of a heavy oil well on primary production.

The two techniques for electrical stimulation of heavy oil wells were introduced earlier and shall be referred to as the *Inductive* and *Resistive* methods. The wellbore configurations for these methods are summarized in Figures 2 and 3, respectively. The fundamental electro-thermal differences between the methods are:

1. For the *Inductive* method the current used to generate heat is induced in the casing using an induction tool (no current flows in the reservoir). The large induced currents create heat due to hysteresis and ohmic losses in the steel casing.
2. For the *Resistive* method, current is forced to flow in the reservoir between electrodes. Heat is generated in the reservoir as a result of ohmic losses associated with ionic conduction through the continuous water phase.

Typically in the *Inductive* method, an induction tool is retrofitted into an existing wellbore and placed where it is determined that heating will be beneficial. This may be near the intake of a progressive cavity pump so that the viscosity of the oil is reduced and the pump can be operated at a higher velocity. The induction tool may be located in the production tubing of a well to prevent wax from precipitating out of the oil. As well, the induction tool can be located adjacent to the heavy oil formation where an increase in temperature of the oil can have a dramatic effect on oil viscosity and the productivity of the well.

Typically in the *Resistive* method, an electrode is permanently located in direct contact with the oil formation. The exact location of the electrode is a matter of engineering design, with the heating objective being the reduction of the oil viscosity, thus increasing the productivity of the well. The salient features of the *Inductive* and *Resistive* methods are summarized in Table 1.

Numerical simulation of the two heating methods was carried out using the computer program TETRAD[7] to demonstrate the thermal responses and productivity increases that may be expected from electrical stimulation. In both cases the pump is located 10 m above the top of the reservoir. The wellbore hydraulics between the pump and reservoir are modelled. The Base Case assumes that the well has a *skin* of 3 and the operating fluid-level is 11 joints above the intake of the pump. The input data are summarized in Table 2.

Figure 4 compares the temperature distribution established in the reservoir for the two methods after five years of heating. The salient difference is the distance into the reservoir that heat has penetrated. We define r_h as the heated radius, equal to the distance into the reservoir at which the temperature has increased by 10˚ C. At this distance the oil viscosity has been reduced by about a factor of four. The heated radius in the reservoir using the *Inductive* method is less than 2 m. The *Resistive* method has a heated radius of about 11 m.

TABLE 2

Property	Value	Units
Spacing Unit	16	Ha per well
Reservoir Thickness	20	metres
Porosity	0.30	fraction
Permeability	10,000	mD
Dead Oil Viscosity	10,000	mPa·sec
Initial Temperature	20	˚ C
Initial Pressure	5,000	kPa
Initial Fluid Level	11	Joints
Stimulated Fluid Level	5	Joints
Initial Skin	3	
Input Power *Inductive/Resistive*	10/20	kW

Figures 5 and 6 compare the production responses of the wells to the electrical stimulation methods with the Base Case production. The stimulation mechanisms for either the *Inductive* or *Resistive* methods are one or a combination of the following:

1. Increase in the effective wellbore radius to the heated radius r_h.
2. Reduction in pressure drops associated with wellbore hydraulics.
3. Removal of near wellbore skin effects, such as visco-skin[8].
4. Improvement of pumping efficiency.

In Figures 5 and 6, the *Stimulation* plots refer to the first two mechanisms. The *Skin Removal* plots include the removal of skin effects. The *Improved Drawdown and Skin Removal* plots show the results of reducing the drawdown pressure at the pump. The difference between the two methods is that the peak stimulation rate for the *Resistive* method is greater than for the *Inductive* method and is sustained for a longer period of time. This result is a direct consequence of the fact that heat penetrates further into the reservoir and that heat penetration continually increases with time.

The paradigm that electrical power is a prohibitively expensive form of energy for use in the recovery of hydrocarbons is examined by calculating the economics of the *Inductive* and *Resistive* stimulation methods. The third table summarizes the input data and results obtained for the different electrical heating methods

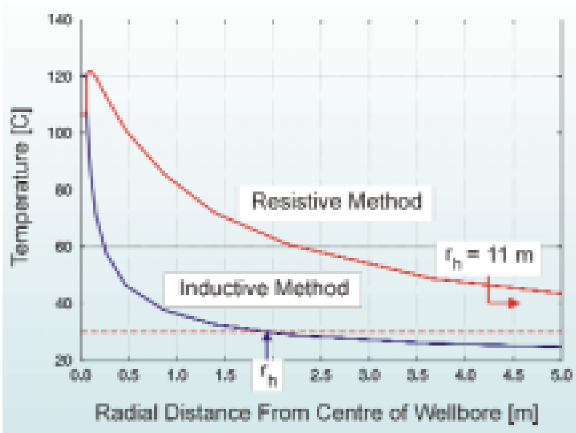

FIGURE 4: Temperature distributions in the reservoir for the *Inductive* and *Resistive* methods.

FIGURE 5: Production responses from a heavy oil well using the *Inductive* method.

and compares them against the Base Case. No inflation in either the operating costs or capital costs is assumed. An industry economic model was used to make the calculations. For this comparison, the electrical stimulation production forecast that was used assumes that all four stimulation mechanisms enumerated above were present. The Net Present Value at 15% (NPV@15%) is based on the pre-tax cash flows.

The increase in operating costs is a direct result of the purchase of electrical power from the power company. In either of the methods, the increase is less than 5% of the Base Case operating costs. The capital costs include all the electrical equipment needed to implement either of the electrical stimulation methods. As the technology matures, it is anticipated that these capital costs will reduce.

The economics indicate that electrical power costs are a small factor in the commercial viability of the technology. Also, the economics demonstrate the strategic advantage of electrical wellbore stimulation. Producing the oil quickly captures the time value of money(see Table 3).

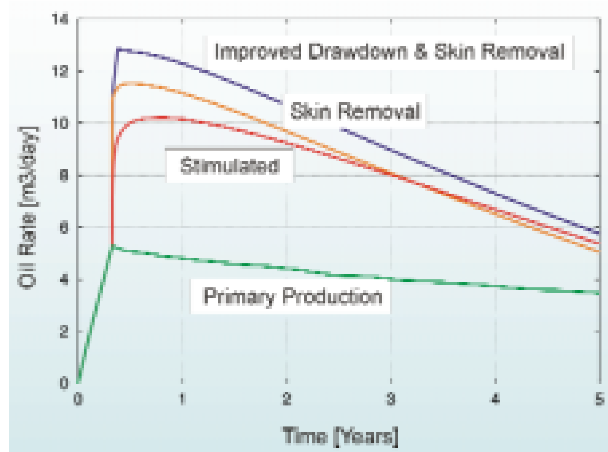

FIGURE 6: Production responses from a heavy oil well using the *Resistive* method.

Electrical Heating for Environmental Remediation

Remediation of soil contamination can be a long and costly operation. It has been demonstrated that heating the soil can greatly accelerate the removal of many contaminants, such as gasoline and other volatile organic compounds. Electrical heating is a viable thermal method for removing contaminants from soil *in situ*[9]. The use of electrical heating at the Turtle Bayou Superfund site in Texas demonstrated that semi-volatile organic compounds could be removed from the contaminated soil in less than four months, whereas non-thermal methods required two to three years. Similar results where achieved at a project in Calgary, Alberta[10].

Electrical soil heating for environmental applications works in synergy with soil vapour extraction and bio-remediation. An increase in temperature increases the vapour pressure of contaminants and forces them into the vapour phase where they are easily recovered from the soil at extraction wells. In the case of bioremediation, every 10˚ C increase in soil temperature doubles the rate at which bio-matter populates and thus the effectiveness of bioremediation.

TABLE 3

Input Data	Base Case	Electrical Heating Method: Inductive	Electrical Heating Method: Resistive
All In Capital Costs	\$250,000	\$325,000	\$350,000
Operating Costs	\$60.00/m³	\$62.31/m³	\$63.68/m³
Power Costs	-	\$0.06/kW·hr	\$0.06/kW·hr
Input Power	-	10 kW	20 kW
Oil Price	\$160/m³	\$160/m³	\$160/m³
Forecast	10 years	10 years	10 years
Cumulative Production	13,150 m³	24,110 m³	29,550 m³
Economic Results			
NPV@15%	\$384,210	\$732,180	\$919,640
Economic Ratios	1.00	1.90	2.40
Reserve Ratios	1.00	1.83	2.25

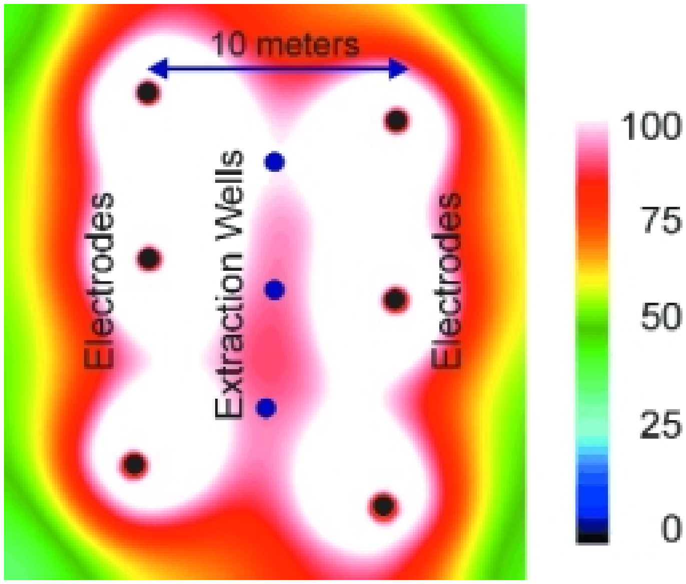

FIGURE 7: Temperature contours in the contaminated soil of a decommissioned gas station after 115 days of electrical heating.

Figure 7 shows the temperature response achieved in the soil after 115 days of electrical heating at the Calgary remediation site, a decommissioned service station. The temperature contours are calculated using a numerical model and matched to the measured electro-thermal data. In the regions where the temperature increase was greater than 40˚ C, more than 95% of the contaminant was removed at the vapour extraction wells.

Summary

In summary, there is vast potential for the use of electrical heating technology in the energy and environmental industries. Electrical wellbore stimulation is continuously evolving and commercialization of the technology will likely take place in the not too distant future. Field pilot tests of electrical wellbore stimulation indicate that the remaining technical challenges are with operational and mechanical issues. Electrical soil remediation has been demonstrated at several sites and is presently listed as a commercially viable technology with the United States Environmental Protection Agency. Electrical heating processes have been extensively studied using numerical models and physically scaled experiments. The notions that electrical power is a prohibitively expensive form of energy are immediately dispelled in review of the economics of the process.

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