

The Viability of Oil Extraction from Trinidad Tar Sands by Radio Frequency Heating: A Simulation Approach

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ABSTRACT

Trinidad has tar sand resources of about 2 billion barrels of oil on land in the Parrylands/Guapo and Brighton areas. With an oil price of over USD 25 per barrel, the commercial extraction of oil from Trinidad tar sands is viable, but it requires a careful study. The relatively small extent of this tar sand (about 10,000 acres and with depths varying from surface to less than 500 feet) and with an oil in place of about 1000 times smaller than the Canadian tar sands, large scale surface mining and in situ methods such as SAGD and VAPEX processes or their variants are not practical and environmentally friendly.

In this study, we explore the viability of oil extraction from unconventional Trinidad tar sands by radio frequency (RF) heating. RF heating does not require an overburden and is cheaper than SAGD and VAPEX; it is also environmentally friendly since no steam, water, and solvents are needed. Studies have also shown that RF heating is uniform and quicker, and it makes a deeper penetration than direct electrical (resistive) heating; thus, an oil recovery between 50 to 80% can be achieved. Preliminary studies have indicated that Trinidad tar sands are wetting, and that permittivity values in the range of 38-100 make it suitable for RF heating.

The COMSOL Multiphysics® software was used to simulate oil sand samples within a copper chamber, and the RF heating was applied via a dipole antenna. Temperature-time heating plots were generated using an operating frequency of 10 MHz and a current of 50 amperes. These data and the physical properties of the tar sands were then simulated using the CMG software. The results indicated an oil recovery in the range of 30-60%. An energy balance was then conducted, and the results showed that the commercial extraction of oil from Trinidad tar sands by RF heating is viable with an oil price of over USD 25 per barrel.

Keywords: Radio Frequency Heating, Tar Sand/Oil Sand, Oil Extraction, Simulation Study, Unconventional

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INTRODUCTION

Tar sands or oil sands are defined as sands that contain oils which have an API gravity of less than 10° [1] and a viscosity greater than 10,000 cP [2]; they are also non-mobile in reservoir conditions. Tar sand deposits are widely distributed throughout the world in countries such as Canada, Venezuela, the United States, Russia, and Trinidad [3]. To date, techniques applied to recover oil from tar sands deposits are mining and in situ methods such as steam assisted gravity drainage (SAGD), vapor extraction (Vapex), and direct heating [4]. The selection depends mainly on the depth of the deposit and the cost required to recover the oil and to protect the environment.

Radio frequency heating (RFH) is an oil recovery technique that is currently in the pilot stages of testing to recover oil from the Alberta tar sands [5]. The pilot well is horizontal and 100 m in length into a mine face. The RF generator was set at an operating frequency of 6.78 MHz (within the ISM Band), and the temperature increased to 130 °C after 34 days of heating. A recovery rate of up to 80 bbls/day was achieved, and the recovery factor was found to be 65% for a drainage radius of 6 meters. The Alberta oil sands are oil-wetting with oil having an API gravity of 8 degrees [5].

In Trinidad, the relatively small extent of our tar sands (about 10,000 acres and with depths varying from surface to less than 500 feet) with an oil in place of about 1000 times smaller than the Canadian tar sands indicates that large scale surface mining and in situ methods such as SAGD and VAPEX processes or their variants are not practical or environmentally safe [6-7]. VAPEX and SAGD processes require an overburden to prevent the escape of injected fluids, and since the majority of Trinidad's tar sands are

exposed at surface, these processes are not applicable. Large scale mining would specifically present a major environmental issue due the water requirements for the Clark hot water washing process and the oily waste water produced upon bitumen extraction.

RFH does not require an overburden, so it can be applied to Trinidad's exposed tar sands. This process is cheaper than SAGD and environmentally friendly since no steam and water is needed. Studies [8] have also shown that RF heating is uniform and quicker; it has deeper penetration and lower heat losses than direct electrical heating. In Trinidad, the oil sand is water wetting and has gravity in the range of 4.6 to 8.0 °API.

Preliminary studies conducted by Hosein et al. [6-7] on Trinidad tar sands indicated a maximum recovery of 20% by weight from solvent extraction using a Soxhlet and a maximum of 10% by weight from electrical heating at a temperature of about 525 °C using a thermogravimetric analyzer (TGA). This paper presents phase one of oil sand project of Trinidad which is being conducted in the Petroleum Studies Unit at the University of The West Indies (UWI), Trinidad and Tobago. In this phase, a simulation study was conducted to determine the feasibility of oil recovery from Trinidad tar sands by RFH using COMSOL Multiphysics® software and then CMG® (Computer Modelling Group) STARS. Phase two will involve experimental testing of actual oil sand samples in a chamber to verify the simulated results. This study will also be the first to investigate the effect of RFH on oil recovery for water wetting sands.

In this study, the models of oil sand samples were created using the known properties of oil sand of Trinidad. Properties such as electromagnetic permeability, density, thermal conductivity,

electrical conductivity, and most importantly complex permittivity were used in COMSOL Multiphysics® to create the most representative oil sand model. RFH was applied to the samples via a dipole antenna, and the heating effect was evaluated in COMSOL. The duration of heating and operational frequencies were varied (0.25-13.56 MHz) to observe the extent of heating through temperature distribution and the radial distance of heating.

The reservoir properties of oil sand (porosity, permeability, and oil and water saturation) from a cored tar sand reservoir in south Trinidad (Parrylands) were then used to model an oil sand reservoir in CMG® STARS. The heating effect simulated with COMSOL was then replicated as a heater well in STARS. Both vertical and horizontal wells were used in separate runs to evaluate the oil production achieved by RFH and ultimately the oil recovery.

EXPERIMENTAL PROCEDURES

THEORY

Radio Frequency Electromagnetic Waves

The theory of electromagnetic waves was first put forth 150 years ago by an English scientist, James Clerk Maxwell, in 1861 and verified by Heinrich Hertz in the late 1880's. In Maxwell's study, he found out that electrical fields and magnetic fields couple together to form electromagnetic waves (Figure 1) [9].

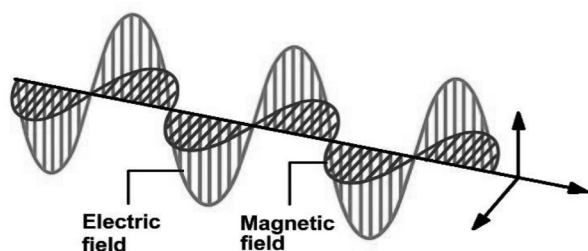


Figure 1: Components of an electromagnetic wave (after National Aeronautics and Space Administration, 2010 [9]).

By itself, an electric field is static; a magnetic field is static too. However, Maxwell discovered in 1861 that in an EM (electromagnetic wave), a change in the magnetic field will induce a change in the electric field and vice-versa. Furthermore, it was concluded that an electromagnetic wave exists when the changing magnetic field causes a change in the electric field, which then causes another change in the magnetic field. This occurs continuously, and hence the wave can be never-ending. An electromagnetic wave will continue indefinitely until it is absorbed by a material [9]. The frequency range of electromagnetic waves form the electromagnetic spectrum ranges from extremely low frequencies of a few Hertz to Gamma rays at 100 s of Exa-Hertz [10]. The wavelength (λ) of an electromagnetic wave is related to its frequency (f) by the following relationship:

$$c = \lambda f \quad (1)$$

where, the speed of light in free-space is $c \approx 3 \times 10^8$ m/s. Wavelengths range from many thousands of kilometers for frequencies at the lower end of the electromagnetic spectrum to picometers at the upper end [10]. Radiations whose frequencies range from 3 kHz to 300 MHz are referred to as radio frequencies (RF), whilst those ranging from 300 MHz to 300 GHz are microwaves (MW). Electromagnetic radiation consists of both radio-frequency waves and microwaves [11].

Radio Frequency Heating (RFH)

RF heating is a coupling between electromagnetic fields and heat transfer, where the transient temperature rises due to electromagnetic fields, and temperature-dependent material properties are considered.

Heat is generated by radio frequency electromagnetic

waves through the orientational polarization of polar components in a material undergoing RF heating. When a material is placed between two metal plates, an electrical capacitor is formed. The material becomes a “lossy” dielectric (hence the alternative name “Dielectric Heating” is also used) and absorbs energy from an RF generator which is connected across the two plates. The RF heating process depends upon the ionic conductivity of the material being heated.

The effect is analogous to that of two bar magnets where polar molecules have positively and negatively charged ions. If the two electrode plates are charged positive and negative respectively, the material molecules will tend to line up all in one direction. If the charge on the plates is then reversed, they will tend to flip around and line up in the opposite direction. Figure 2 shows the way in which this phenomenon happens. The continuous reversal of polarity causes frictional heating within the material and results in overall heating of the material [12]

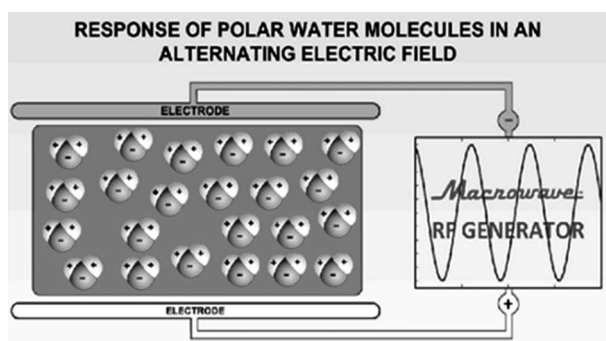


Figure 2: Reversal of polarity (after Radio Frequency Company, 2014 [12]).

RFH Field Tests

Published literature indicates that RFH has the potential to be a commercially viable EOR process

for oil sands. Mukhametshina et al. [13] summarized some of the basic experiments performed in the past in Russia, the USA, and Canada to help with understanding scientific boundaries of RFH technology. Some of the first field work was performed in Yulmirovskoye field of Russia in the 1980's, where 20 kW of power was applied for 36.5 hours, and the bottomhole temperature increased from 282 K to 389 K (from 9 to 116 °C). This change in temperature was observed close to antenna well in a radial distance of 5 meters. However, by increasing the power to 60 kW over 32 hours, the bottom hole temperature was found to be 583 K (310 °C), and 5 meters away, an adjacent well was heated to 318 K (45°C).

Bridges et al. [14] showed that field tests were also conducted on the Utah tar sands of the Asphalt Ridge. Formation temperatures exceeded 473 K (199 °C), and 30 to 35% hydrocarbon recovery was achieved in just 20 days. It was then estimated that 50 to 70% recovery could be achieved in a 6-month period. Bridges [14] recommended that RFH be used in conjunction with other in situ recovery techniques to maximize efficiency for its given application.

Ovalles et al. [11] looks at dielectric heating in Venezuela (Trinidad and Tobago's closest neighbor). A numerical model of a heavy crude (7.7 °API), which has a similar oil gravity to bitumen from Trinidad oil sand, shows that 76% recovery is achieved after a 10-year period by applying 160 kW of power at 915 MHz. The viscosity is reduced from 270 cP at 130 °F (54 °C) to 92 cP at 275 °F (121 °C).

Limitations of RFH

Limitations and technical challenges with RFH include:

- Oil itself has a low dielectric constant and is a weak absorber of electromagnetic energy.
- Conventional downhole casing and equipment disrupt EM waves. The casing for an RF producer needs to be made out of materials that are good insulators and have excellent dielectric properties (for example, Teflon and fiberglass).
- If the formation is close to the surface, there may be a need for some forms of shielding when using frequencies above 50 MHz.

Simulating RFH

The COMSOL Multiphysics software simulates RFH by combining electromagnetics and heat transfer in materials. The Maxwell equations presented in 1861 are used to compute the electromagnetic energy and its propagation in materials [15]. Maxwell equations are a collection of partial differential equations that describe the electric and magnetic fields of EM waves. The equations of Maxwell are used to state the relationships between the fundamental electromagnetic quantities as follows:

$$\nabla \cdot H(r, t) = J(r, t) + \partial D(r, t) / \partial t \quad (2)$$

$$\nabla \cdot E(r, t) = -\partial B(r, t) / \partial t \quad (3)$$

$$\nabla \cdot B(r, t) = 0 \quad (4)$$

$$\nabla \cdot D(r, t) = \rho(r, t) \quad (5)$$

$$B(r, t) = \mu_0 [H(r, t) + M(r, t)] \quad (6)$$

$$J(r, t) = \sigma [E(r, t) + E_i(r, t)] \quad (7)$$

$$D(r, t) = \epsilon_0 E(r, t) + P(r, t) \quad (8)$$

where:

$\nabla \cdot$ is the curl operator (a measure of the rotation of a vector field);

∇ is the divergence of the electric field;

$H(r, t)$ is the magnetic field intensity in A/m;

$E(r, t)$ is the electric field intensity in V/m;

$B(r, t)$ is the magnetic flux density in T;

$D(r, t)$ is the electric flux density in C/m²;

$J(r, t)$ is the electric current density in A/m²;

$\rho(r, t)$ is the electric charge density in C/m³;

$M(r, t)$ is the magnetization in A/m;

$E_i(r, t)$ is the impressed electric field in V/m;

$P(r, t)$ is the polarization in C/m²;

μ_0 is the permeability of vacuum in H/m

($\mu_0 = 4\pi \cdot 10^{-7}$ H/m);

σ is the conductivity in S/m;

ϵ_0 is the permittivity of vacuum in F ($\epsilon_0 = 8.854 \cdot 10^{-12}$ F/m) [16].

The first equation of Maxwell (1861), Equation 2, states the Ampere's (1823) law in differential form which represents the currents in conductors or eddy currents flowing in conducting materials, and time-varying electric fields generating magnetic fields. Equation 3 is the differential form of Faraday (1831) law. This states that the time-varying magnetic field induces electric field [14].

Equation 4 states that the magnetic field is divergence-free; in other words, free magnetic charges do not exist physically, and magnetic flux lines close upon themselves. This is the magnetic Gauss (1867) law. Equation 4 is the electric Gauss' (1867) law. This means that the source of electric field is the electric charge, and electric flux lines start and close upon the charge [16].

COMSOL Multiphysics then computes heat transfer and heat losses in the material. Heat transfer is defined as the movement of energy due to a difference in temperature [15]. It is characterized by the following mechanisms:

- Conduction: where the heat flux is proportional to the temperature gradient.
- Convection: where the heat dissipation is described by a heat transfer coefficient.

Radiation: where the heat transfer by radiation takes place through the transport of photons [15].

The heat equation is as follows:

$$\rho C_p \left(\frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla) T \right) = -(\nabla \cdot \mathbf{q}) + \tau : \mathbf{S} - \frac{T}{\rho} \frac{\partial \rho}{\partial T} \left(\frac{\partial P}{\partial t} + (\mathbf{u} \cdot \nabla) P \right) + Q \quad (9)$$

Where:

ρ is the density (kg/m³);

C_p is the specific heat capacity at constant pressure (J/(kg·K));

T is absolute temperature (K);

$\mathbf{u}$ is the velocity vector (m/s);

$\mathbf{q}$ is the heat flux by conduction (W/m²);

p is pressure (Pa);

$\mathbf{T}$ is the viscous stress tensor (Pa);

Q contains heat sources other than viscous heating (W/m³);

$\mathbf{S}$ is the strain-rate tensor (1/s):

$$\mathbf{S} = \frac{1}{2} (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \quad (10)$$

Antenna Sizing

The following equations show how the frequency is related to the wavelength. The length of a dipole antenna arms are then selected to be a quarter of calculated wavelength.

The wavelength (λ) depends on the velocity of the wave (c') and the frequency (f), and is determined by the following equation:

$$\lambda = c' / f \quad (11)$$

where:

λ is the wavelength;

c' is the velocity of the wave;

f is the frequency;

Electromagnetic waves are able to propagate through dielectric media with varying amounts of absorption and reflection occurring. The speed, c' , of electromagnetic waves propagating through a dielectric medium is given by:

$$c' = c / \sqrt{k} \quad (12)$$

where:

c' is the speed of the electromagnetic wave;

k is the dielectric constant of the medium in question (usually more than 1 for dielectric materials);

c is the velocity of light in a vacuum [15].

Permittivity

Permittivity describes the interaction of a material with an electric field. Dielectric permittivity is a function of frequency, temperature, and pressure. It should be noted that the permittivity of a formation will change as the pay zone is heated throughout the RFH process [5].

Complex permittivity, ϵ^* , of dielectrics is often expressed as a combination of the real part, ϵ' , (in Farads per meter, F/m), and a bulk conductivity, δ , (in Siemens per meter, S/m). The real part of complex dielectric permittivity (ϵ') characterizes how much energy a material will store, and the imaginary part (ϵ'') characterizes how much energy is lost; the ratio of imaginary part to real part [$\tan(\delta)$] is used as a general measure of the "lossy-ness" of a given material [5].

Electrical conductivity (δ) is related to loss tangent through $\delta = \omega \times \epsilon' \times \tan(\delta)$, where ω is the angular frequency ($\omega = 2\pi f$)³. Conductivity is the inverse of resistivity ($\delta = 1/\rho$), a commonly measured well log which identifies electrically conductive clay/shale or water.

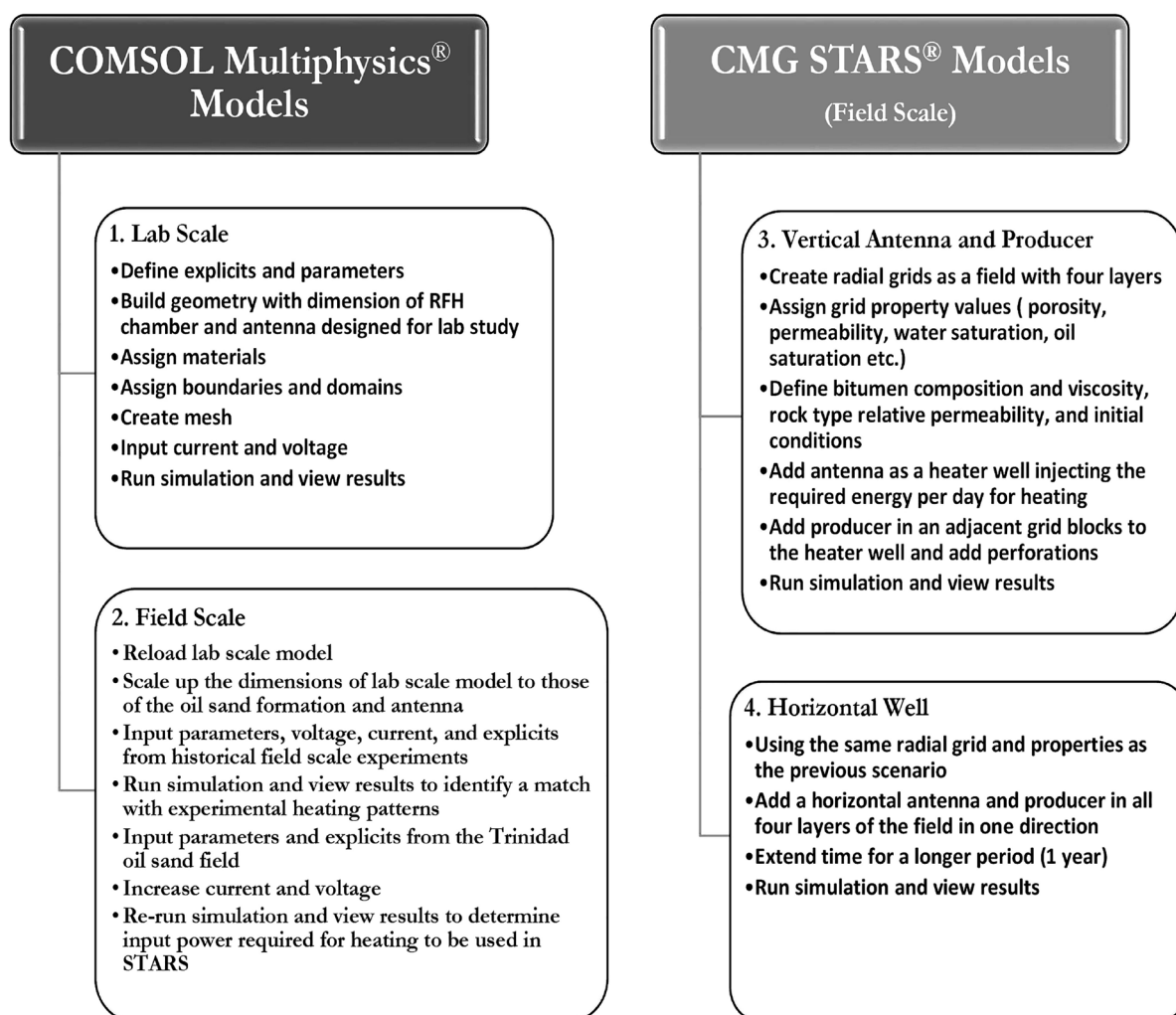


Figure 3: The steps used in the COMSOL Multiphysics® and CMG STARS® Models for the Simulation of RFH.

The flowchart of the simulation of the RFH process is shown in Figure 3.

Electrical conductivity and permittivity measurements were previously conducted on oil sand samples from the Parrylands area of Trinidad. The results (Figures 4a and 4b) show that around 0.25 MHz (250 kHz), the highest permittivity (ϵ_r') of 100 was seen, and at around 10 MHz (10,000 kHz), the permittivity was found to be around 39.5. The highest operating frequency that can be used safely on a lab scale is 13.56 MHz, which corresponds to a

conductivity of 0.071 S/m and a permittivity of 38. In the sensitivity study of this paper, the following ranges are used:

- Operating frequencies (f) in the range of 0.25 to 13.56 MHz;
- Permittivities (ϵ_r) in the range of 38 to 100;
- Conductivities (σ) in the range of 0.062 to 0.071 S/m.

Additional properties of Trinidad oil sands used in this study are shown in Table 1.

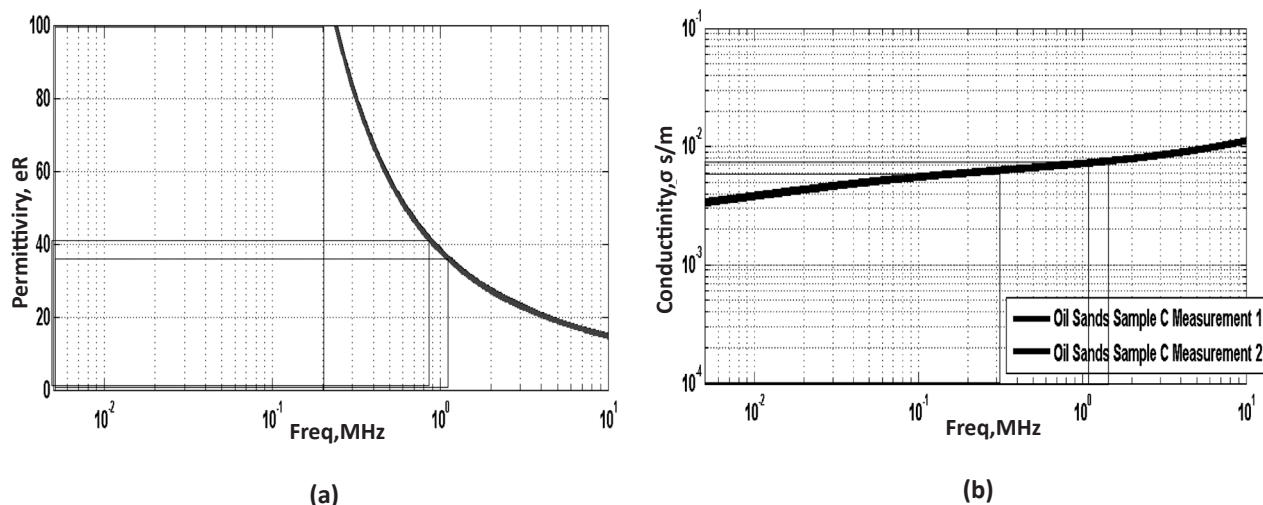


Figure 4: Results obtained from the permittivity and conductivity testing of Trinidad oil sand; (after collaboration between Harris Corporation and the University of the West Indies).

Table 1: Properties of Trinidad (Parrylands) oil sand and bitumen; (modified from Rajpaulsingh [17] and Kuarsingh and Maharaj [18]).

Tar Sand Properties	Average from Core Samples
Porosity (%)	31.7
Permeability (mD)	1181
Water Saturation (%)	24.4
Oil Saturation (%)	63.2
API Gravity	4.6
Viscosity at 100°C (cP)	324
Bitumen Weight (%)	13

RFH Test Chamber Design

Figure 5 shows the major components of the test chamber designed and built to study RFH for Trinidad oil samples in the laboratory. The double cylinder chamber allows for oil sand to be packed between two cylinders. The inner cylinder serves as a casing and separates the coaxial cable or dipole antenna that will emit the EM waves into the oil sand.

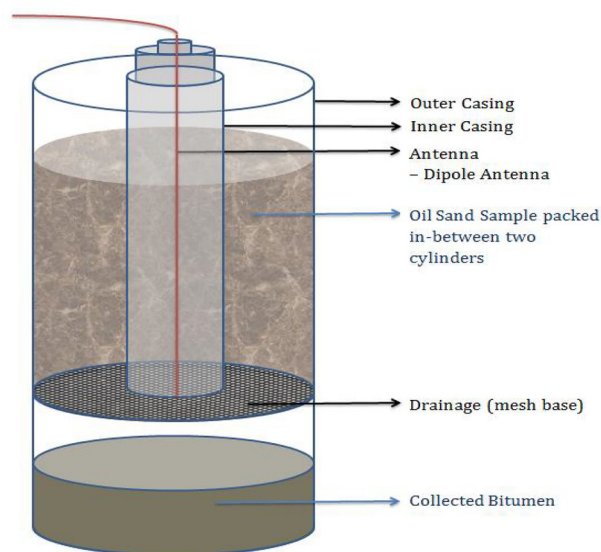


Figure 5: The diagram of the major components of the test chamber designed for RFH.

A transmitter is used to transmit power to the dipole antenna, which in turn radiates electromagnetic energy outwards radially from the antenna and into the oil sand sample. The electromagnetic energy heats the oil sand, so it lowers the viscosity of its bitumen. Due to gravity drainage and the lowered viscosity, the bitumen will then flow past the mesh base and accumulate at the bottom of

the chamber where its volume is measured.

Figure 6 shows the dipole antenna designed for the mine face pilot test conducted in Alberta, which is similar to what will be used for pilot tests on Trinidad oil sands in the field. The following section describes how the simulation of this dipole antenna was carried out.

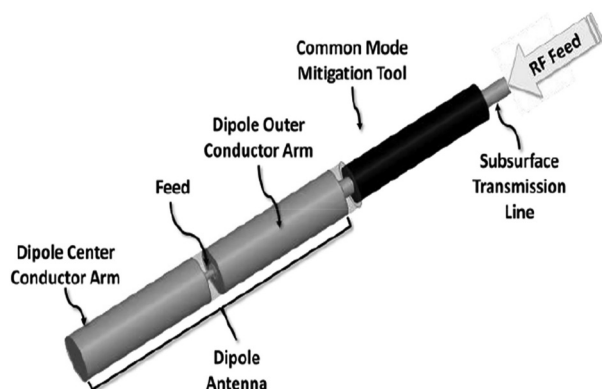


Figure 6: Components of the dipole antenna used in the RFH pilot test in Alberta [19].

Model of RFH with Test Chamber

The dimensions of the chamber used for this simulation are similar to the dimensions of the actual chamber that was built for the experimental studies (laboratory scale) as shown in Figure 7. It has a height of 0.099 m, an annular space of 0.066 m, and a capacity of 0.001 m³ or 1 L.

The simulation of the RFH process of oil sand samples within the test chamber was performed using the COMSOL Multiphysics® software. The RF module and the heat transfer module of this software were used to simulate electromagnetic heating of the oil sand sample. A frequency-transient study was selected to compute temperature changes over time together with the electromagnetic field distribution in the frequency domain. The RFH of the oil sand in the chamber was conducted over a selected period of 24 hours, and the temperature changes were observed.

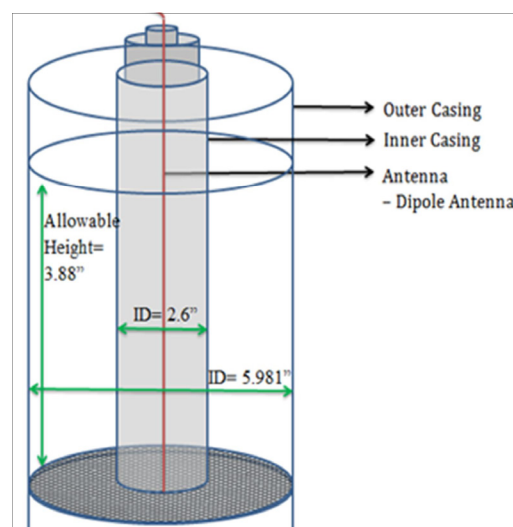


Figure 7: Dimensions and capacity of the section of the test chamber being modeled (lab scale).

An initial set of operating parameters, shown in Table 2, was applied to this lab scale model. An operating frequency of 10 MHz was selected for the simulation as it is within the ISM band, and additional shielding would not be required when conducting the actual experiments. At this frequency, the permittivity of the Trinidad oil sand sample is 39.5, and the corresponding conductivity is 0.07 S/m as shown in Figure 4b.

Table 2: Initial values used in the lab scale RFH model for oil sands.

Parameter	Initial Value
Operating Frequency (MHz)	10
Permittivity	39.5
Conductivity (S/m)	0.07
Current (Amp)	10
Voltage (V)	220

It should be noted that the entire test chamber was not modeled in this simulation study; only the section with the oil sand and antenna was included, and the drainage or antenna feed was not modeled since bitumen recovery cannot be simulated with COMSOL Multiphysics® (See Software Limitations sub-section).

The following subsections show the details of the components which were modeled:

Antenna

A dipole antenna was used to make the RF EM waves resonate into the oil sand sample. This type of antenna consists of two thin metallic rods. The length of the rods is chosen such as to be a quarter of the wave length at the operating frequency. The model of the antenna in COMSOL consists of two thin cylinders each representing the arms of the dipole antenna. For the lab scale model, the free space wave length at the antenna operating frequency is 0.197 m. Thus, each of the antenna arms is 0.049 m long and aligned with the z-axis. The antenna radius is chosen to be 0.002 m (Table 3). A sinusoidal voltage difference is applied at a small cylindrical gap of size 0.00049 m between the antenna arms. This represents the voltage source (Figure 8). The power supply and feed structure were not modeled explicitly, and it was assumed that a uniform voltage difference was applied across these faces. This source induces electromagnetic fields and surface currents on the adjacent conductive faces. The dipole arm surfaces were modeled using the Impedance boundary condition. The antenna is situated in the center of the chamber, similar to the actual chamber design.

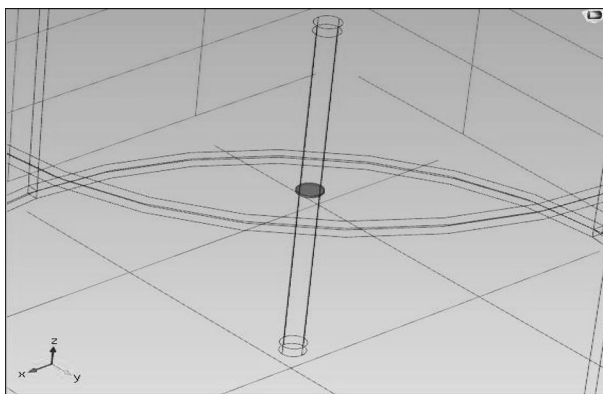


Figure 8: Dipole antenna and the 0.097" gap which acts as the voltage source for the antenna.

Table 3: Dimensions used for the lab scale antenna and chamber.

Name	Expression	Value (m)	Description
lambda0	7.76 in	0.197	Operating wavelength
arm_length	lambda 0/4	0.049	Dipole antenna arm length
r_antenna	arm_length/20	0.002	Dipole antenna arm radius
gap_size	arm_length/100	0.00049	Gap between arms

Oil Sand Sample

The oil sand sample is represented by a solid cylinder surrounding the antenna but within the chamber walls (Figure 9). The conductivity of the hydrocarbon layer is 0.07 S/m, and the permittivity is 39.5 for the initial run. Table 4 shows the additional electrical and thermal properties used to represent the oil sand sample.

Table 4: Properties of the oil sand sample used.

Name	Value	Unit
Density	961.873	kg/m ³
Heat capacity at constant pressure	583	J/(kg.K)
Thermal conductivity	1.5	W/(m.K)
Relative permeability	1	1
Relative permittivity	39.5	1
Electrical conductivity	0.07	S/m

Test Chamber Walls

The outer structure of the chamber (walls and covers) was modeled as a copper surface cylinder (Figure 10) with an external perfectly matched layer (PML) that acts as an absorber for outgoing radiation. The far-field pattern is computed on the boundary between the oil sand and the PML domains.

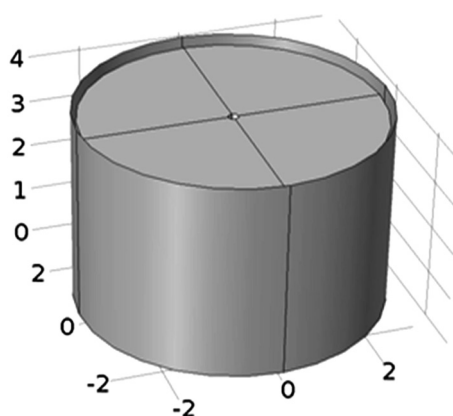


Figure 9: The oil sand sample represented by a solid cylinder.

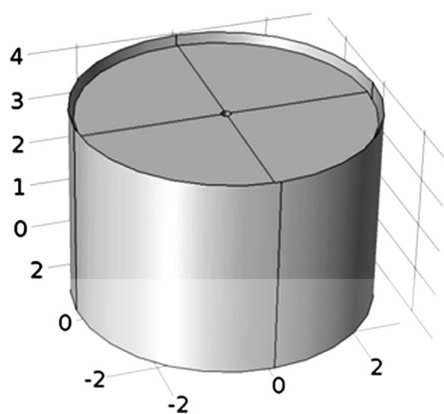


Figure 10: The chamber represented by a surface cylinder with the antenna at its center.

Meshing

The mesh was based on the physics of the model, but it was manually adjusted so that the boundaries of the antenna are meshed more finely (Figure 11).

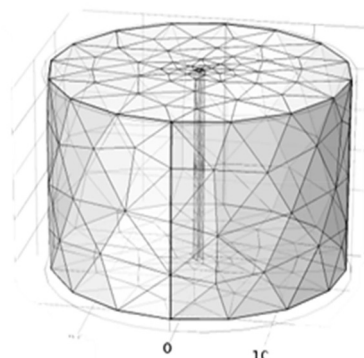


Figure 11: The physics controlled mesh created by COMSOL Multiphysics®.

Software Limitations

While the RF module of COMSOL Multiphysics® allows the evaluation of the heating effect of the dipole antenna by predicting the resultant temperature increase in RFH, this module of the software is unable to evaluate the volume of bitumen that can be recovered from the oil sand sample. The RF module is not designed to model fluid flow through porous media (oil sand), and it looks specifically at the electromagnetic heating of it. Bitumen recovery was evaluated using the reservoir simulation software, CMG® STARS, where the heating effect observed in COMSOL was replicated as a heater well in the oil sand, and oil production was simulated via production wells.

RESULTS AND DISCUSSION

COMSOL Results

The lab scale model shows that by applying RFH to a sample with the properties of oil sand of Trinidad at 10 MHz, at 10 amperes, and for a period of 24 hours, the entire sample was heated to approximately 550 °C due to its small volume (Figure 12).

Table 5 shows that within two hours, the temperature of the oil sand triples. It then steadily increased over time; Figure 13 shows a plot of this. These results prove that RF EM waves can be applied to Trinidad oil sands and result in effective heating.

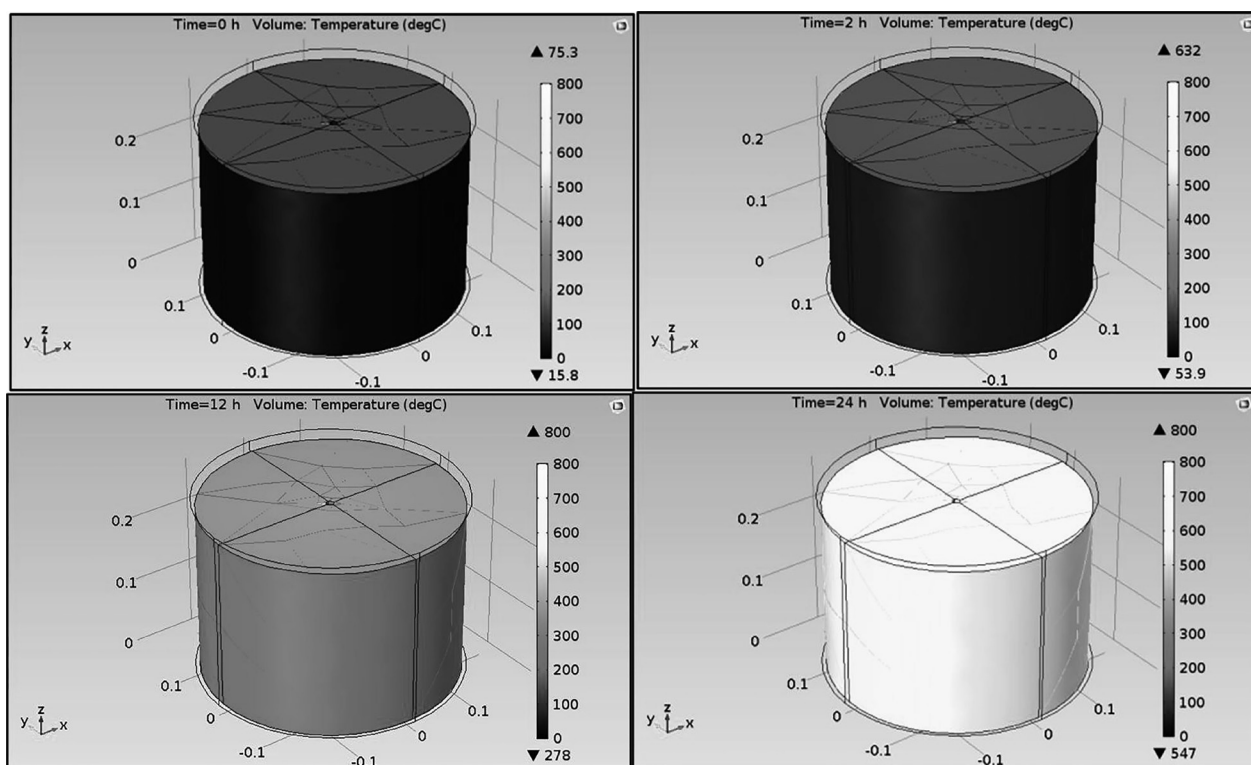


Figure 12: The temperature of the oil sand sample at 0, 2, 12, and 24 hours resulting from RFH within the lab-sized chamber.

Table 5: Average temperature of oil sand resulting from the application of RFH in various intervals.

Time (hr.)	Temperature (°C)
0	20.0
2	64.9
4	109.7
6	154.6
8	199.4
10	244.3
12	289.1
14	334.0
16	378.8
18	423.7
20	468.5
22	513.4
24	558.2

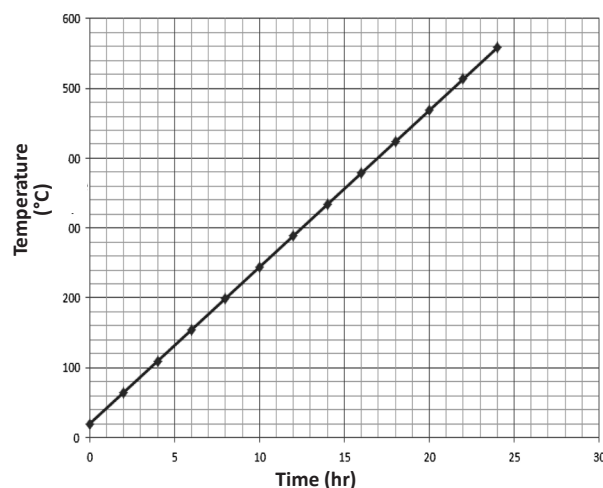


Figure 13: Plot of Average Oil Sand Temperature vs Time for the lab scale RFH model

A cross section or slice plot of the electric field shows that the antenna radiated high electric fields throughout the chamber but stopped at the chamber walls (Figure 14). The chamber walls therefore provided effective shielding on a lab scale (Figure 15).

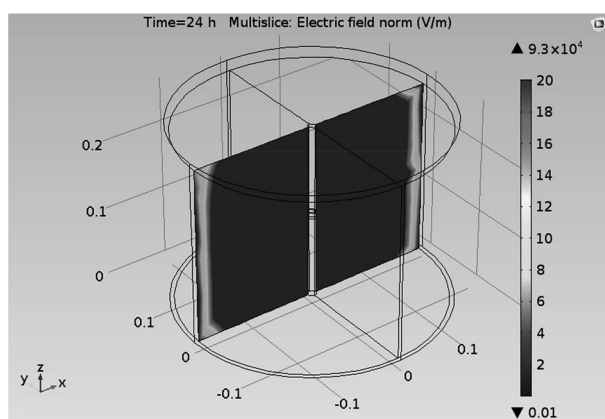


Figure 14: Cross-section of the electric field supplied by the dipole antenna.

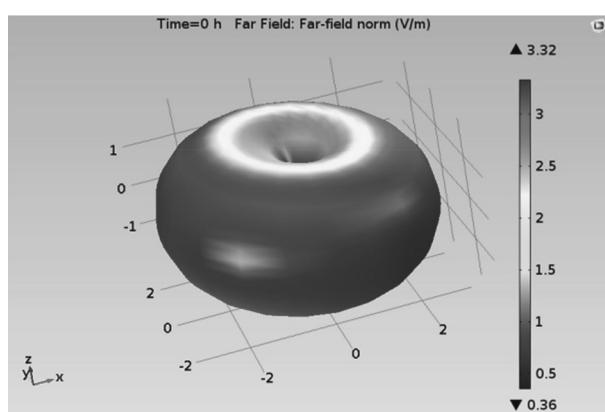


Figure 15: A 3D visualization of the far-field pattern of the dipole shows the expected torus-shaped pattern.

Sensitivity Studies

Field Scale Analysis

The dimensions of the chamber, sample, and antenna were increased to represent a field scale pilot test where the effect of RFH can be observed radially. Table 6 shows the changes made to scale up the model.

RFH was simulated for duration of 30 days in an attempt to match the model data with the data of pilot tests performed in 2014 [20]. In those studies, after 30 days of heating, the temperature of the oil sand was around 130 °C close to the source and heating extended radially to a temperature of 35 °C up to 4 meters away from the antenna.

Table 6: Dimensions-scaled up for simulating RFH of oil sand on a field scale.

Dimension	Lab Scale (m)	Field Scale (m)
Operating wave length	0.197	22
Dipole antenna arm length	0.049	5.5
Dipole antenna arm radius	0.002	1.1
Gap between arms	0.00049	0.05

In order to simulate a similar heating effect, the same operating parameters and reservoir conditions from the pilot test were used. The operating frequency was changed to 6.78 MHz instead of 10 MHz, and a permittivity of 8 was used instead of 39.5; conductivity of 0.01 S/m was applied instead of 0.07 S/m. By applying a current of 10 amps, Figure 16 shows that the history match model created in COMSOL Multiphysics® conforms to pilot tests and the simulation models performed in 2014 [20].

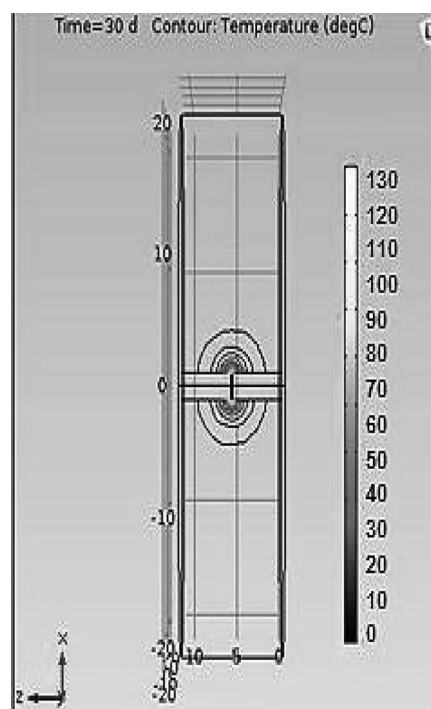


Figure 16: Horizontal view of isothermal contours showing heating radially up to 4 m away from the source after 30 days.

Similar heating was observed from the isothermal contours plot of Figure 16. After 30 days of heating, temperature increased to 33 °C; 4 meters away from the source, and close to the source a temperature of 130 °C was observed.

The model was then edited to include Trinidad oil sand properties (permittivity=39.5 and conductivity = 0.07 S/m) and the selected operating frequency (10 MHz). At this point, it was found out that at a current of 10 amperes, the electric field was small (Figure 17), and no change in temperature in the majority of the sample was observed. The power supply was too low to provide the required heating for this large sample.

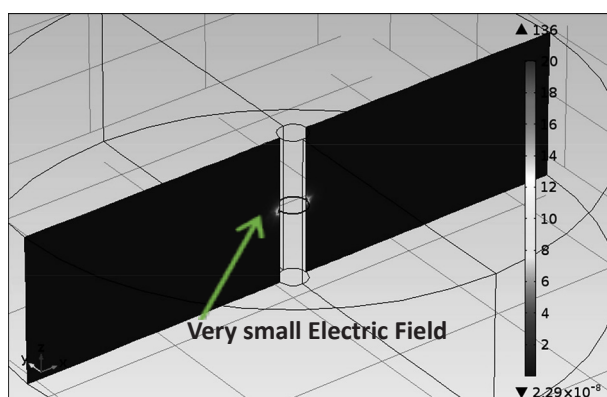


Figure 17: The electric field slice plot at a current of 10 amperes where the electric field is limited and very close to the RFH source.

Hosseini et al. [6-7] demonstrated that the maximum oil recovery from Trinidad oil sands occurs at around 525-530 °C since its bitumen consists of mainly heavy components (C10 to C21). This temperature was used for heating the sample by increasing the current at 5 ampere intervals until temperatures around 500 °C began radiating from the antenna. The current supply was eventually amplified to 50 amperes which significantly increased the electric field after 60 days of heating as shown in Figure 18.

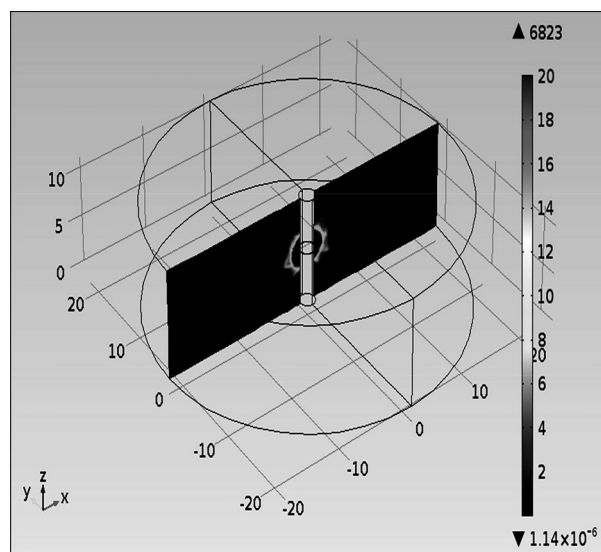


Figure 18: Increase in electric field to 50 amperes.

The oil sand temperature also increased significantly in the sample. Successful heating uniformly occurred outwards from the source, as shown in Figures 19 and 20. Close to the source (antenna), very high temperatures (450-500°C) were generated. Figure 20 shows that after 60 days, heating extends radially 4 to 5 m away from the source. The increase in temperature at this distance was approximately 200°C.

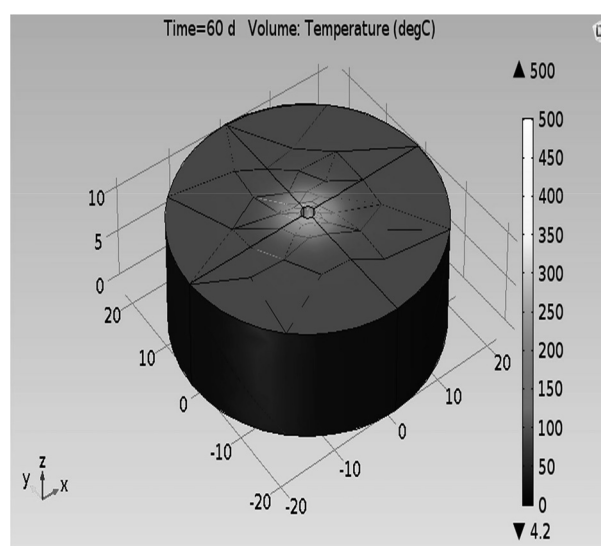


Figure 19: Temperature increase in oil sand sample.

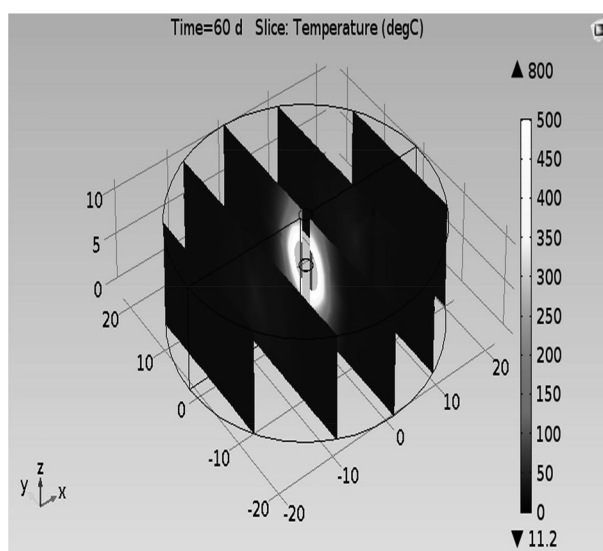


Figure 20: Slice plot showing the radial distance of heating provided by the source.

The average temperature and maximum temperature of the oil sand samples over time are shown in Table 7.

Table 7: Temperatures of the oil sand sample recorded over time for this field scale analysis.

Time (day)	Average Temperature (°C)	Maximum Temperature Close to Source (°C)
0	20.0	64.6
5	22.0	526.9
10	24.1	530.7
15	26.1	534.9
20	28.1	545.4
25	30.1	552.8
30	32.2	559.3

Frequency, Permittivity, and Conductivity

Previous measurements show that by varying the operational frequency, the electrical permittivity and conductivity changed as well. The initial measurements of permittivity and conductivity at an operating frequency of 10 MHz were respectively 39.5 0.07 S/m. A frequency of 10 MHz was used since this falls within the ISM Band and does not require intense shielding to be safe.

However, the highest safe operating frequency used in these studies is 13.56 MHz. The lowest measured frequency was 0.25 MHz.

These frequencies (0.25, 10, and 13.56 MHz) correspond to the permittivities ($38 < \epsilon_r < 100$) and conductivities ($0.062 < \sigma < 0.071 \text{ S/m}$) shown in Table 8. The three frequencies were used to observe the heating impact by applying RFH to the lab scale model created in COMSOL previously.

Table 8: Variation of permittivity and conductivity versus operating frequency.

Parameter	Low Case	Base Case (Initial Value)	High Case
Operating Frequency (MHz)	0.25	10	13.56
Corresponding Permittivity	100	39.5	38
Corresponding Conductivity (S/m)	0.062	0.07	0.071

In the field, oil sand permittivities and conductivities vary from one location to the next one. Furthermore, the permittivity and conductivities of the formation will change as the pay zone is heated throughout the RFH process as the conductive water present in the formation is continuously vaporized until desiccation occurs [5] (see Theory-Permittivity). It is therefore essential to perform these sensitivity studies and determine the effect of RFH on oil sand with varying permittivities and conductivities.

The results from this sensitivity analysis are plotted in Figure 21. It shows that at high operating frequencies, the permittivity values are low, and high temperatures are generated with time. At low operating frequencies, the permittivity values are high, and low temperatures are generated with time.

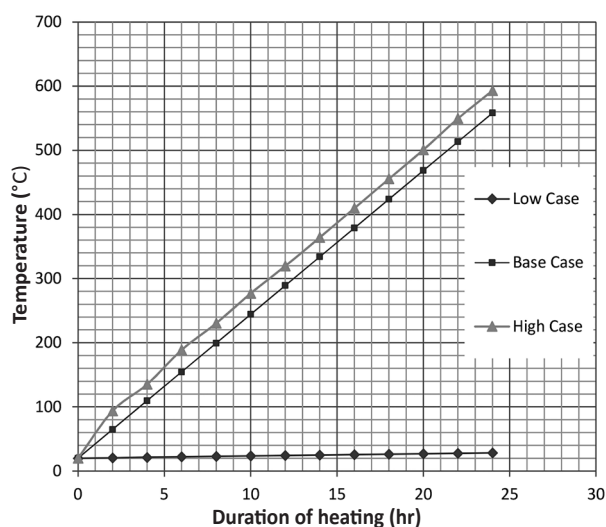


Figure 21: Sensitivity analysis of oil sand temperature versus time.

STARS® Modelling and Results

Vertical Well Orientation

The heating effect observed by applying RFH to a simulated Trinidad oil sand in COMSOL Multiphysics® was then replicated in CMG STARS®. A section of oil sand was modeled as a four layer oil sand reservoir.

Each layer was assigned different reservoir properties based on well logs conducted on Trinidad oil sands in 1989. The 4 layers with their assigned dimensions and reservoir properties are shown in Table 9.

The water saturation data in the model plays an important role in RFH. As heating progresses, the temperature of the formation and the water saturation change, thereby changing the properties of the formation, and consequently the EM field pattern. This is because the electrical permittivity and conductivity of the formation depend on water saturation. Therefore, less water means reduced permittivity and conductivity in the formation. During RFH, any water present is heated to 100 °C (water boiling point), and it is then converted to steam, which can overheat a section of the formation to higher temperatures. As more water is converted to steam the region becomes desiccated, and the EM waves propagate further out away from the antenna to where water is present. Therefore, the presence of water is essential for the propagation of EM energy (and heat) into the formation. A larger desiccation zone causes the expansion of the heating zone which is essential for oil recovery.

The salinity of the water also plays an important role in RFH. A higher salinity means that the boiling point of the water can exceed 100 °C, which allows the formation temperature to be elevated even further. The salinity of the oil sand was selected to be 10,000 ppm.

Table 9: Oil sand reservoir properties (after Rajpaulsingh, 1989 [17]).

Layer	Grid Top (m)	Grid Thickness (m)	Porosity	Permeability (mD)	Oil Saturation	Water Saturation	Temperature (°C)	Pressure (psi)
1	42.7	9.4	0.27	948	0.897	0.103	16.7	63
2	52.1	14.3	0.365	1700	0.777	0.233	17.0 (Ref. T)	76.9 (Ref. P)
3	66.4	30.5	0.337	2600	0.813	0.187	17.4	98
4	96.9	11.0	0.353	3060	0.633	0.118	18.2	143.1

The oil sand reservoir model incorporated into the actual core depth of 108 meters (354 ft.) and extended radially to a radius of 20 meters. Figure 22 shows the RFH antenna placed at the center of a section of the reservoir. The vertical production well was placed 0.25 m away since producing and heating from a single grid block leads to errors in STARS®. Placing the producer just a small distance away from the antenna is comparable to producing from the antenna wellbore, as is performed in the actual field studies.

The heat equation (see Theory: Simulating RFH) used by the COMSOL Multiphysics determines the heat sources or the power required for heat generation (Q W/m³). COMSOL was used to determine that 11,500 Watts was required for electromagnetic heating of this field-scale volume of sample. Therefore, the antenna was set to operate 11.5 KW per day for the field-scale model. This means that approximately 9.9×10^8 J (or 0.9×10^6 BTU) of energy per day is being received by the formation.

The Appendix contains an energy evaluation showing the details of energy consumption for the application of RFH in this field, and the economic evaluation gives a brief assessment of the expected cost.

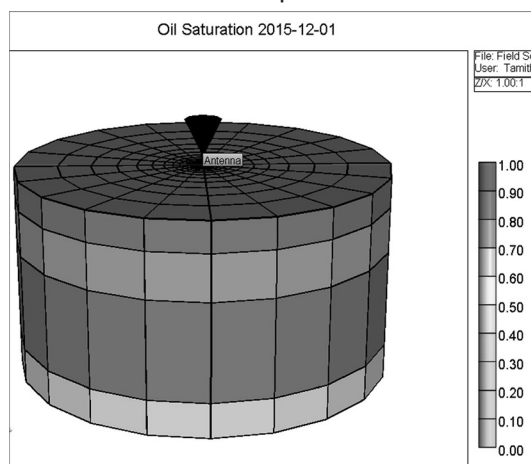


Figure 22: 3D diagram of the cylindrical section of the oil sand reservoir with a centrally located RFH antenna.

The water wetting properties of the oil sand was taken into account by modeling the oil sand as a water wet rock type 1 (see Figure 23) with the relative permeability data shown in the Figure 24.

Rock Types	
Rock Type	1
☐ Use Interpolation Sets	
Rocktype Properties Relative Permeability Tables Hysteresis Modelling Relative Permeability End Po	
Rock Fluid Properties	
Rock Wettability	Water Wet
Method For Evaluating 3-Phase KRO	Stone's Second Model
Interpolation Components (INTCOMP)	☐ Interpolation NOT enabled
Rock-fluid interpolation will depend on component:	
Phase from which component's composition will be taken:	
Foam Interpolation Parameters	
Critical component mole fraction (FMSURF)	

Figure 23: Rock type 1 which describes that the oil sand was selected to be water wet.

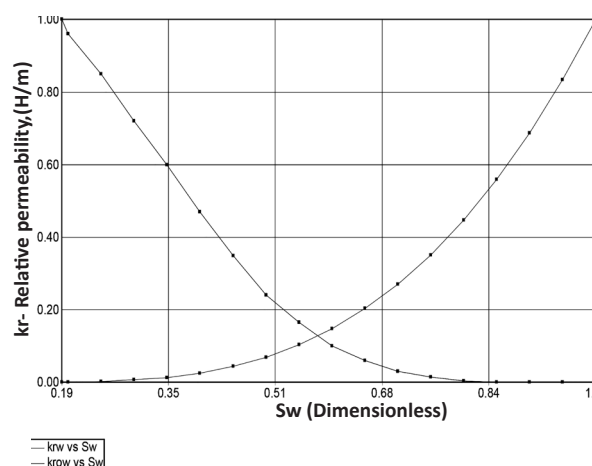


Figure 24: Relative permeability versus water saturation which indicates that the oil sand is water wet.

Upon applying RFH to four different layers of the reservoir in STARS®, the observed resulting changes in temperature were in accordance with that observed in the COMSOL field-scale model. After a period of 60 days, the temperature near the wellbore was approximately 500 °C and heating extended radially up to 4 m away from the antenna wellbore to approximately 200 °C (Figure 25).

Figure 26 shows the oil saturation of the heated zone which has been reduced significantly from

73% to 25 % over 60 days in all 4 layers of the reservoir, regardless of the varying reservoir properties. The depleted zone has a similar pattern to the heating patterns of Figure 25.

Figure 27 shows a plot of the oil rates and cumulative production with time. From this, an average oil rate of 8 bbls/day was estimated, and the cumulative

production at the end of the simulation (60 days) was found to be 480 bbls. Figure 28 shows the recovery factors for the section being drained by the vertical producer around the antenna (3.5 m away from source) over the 2-month period. The recovery factor steadily increased until it began to plateau at around 58%.

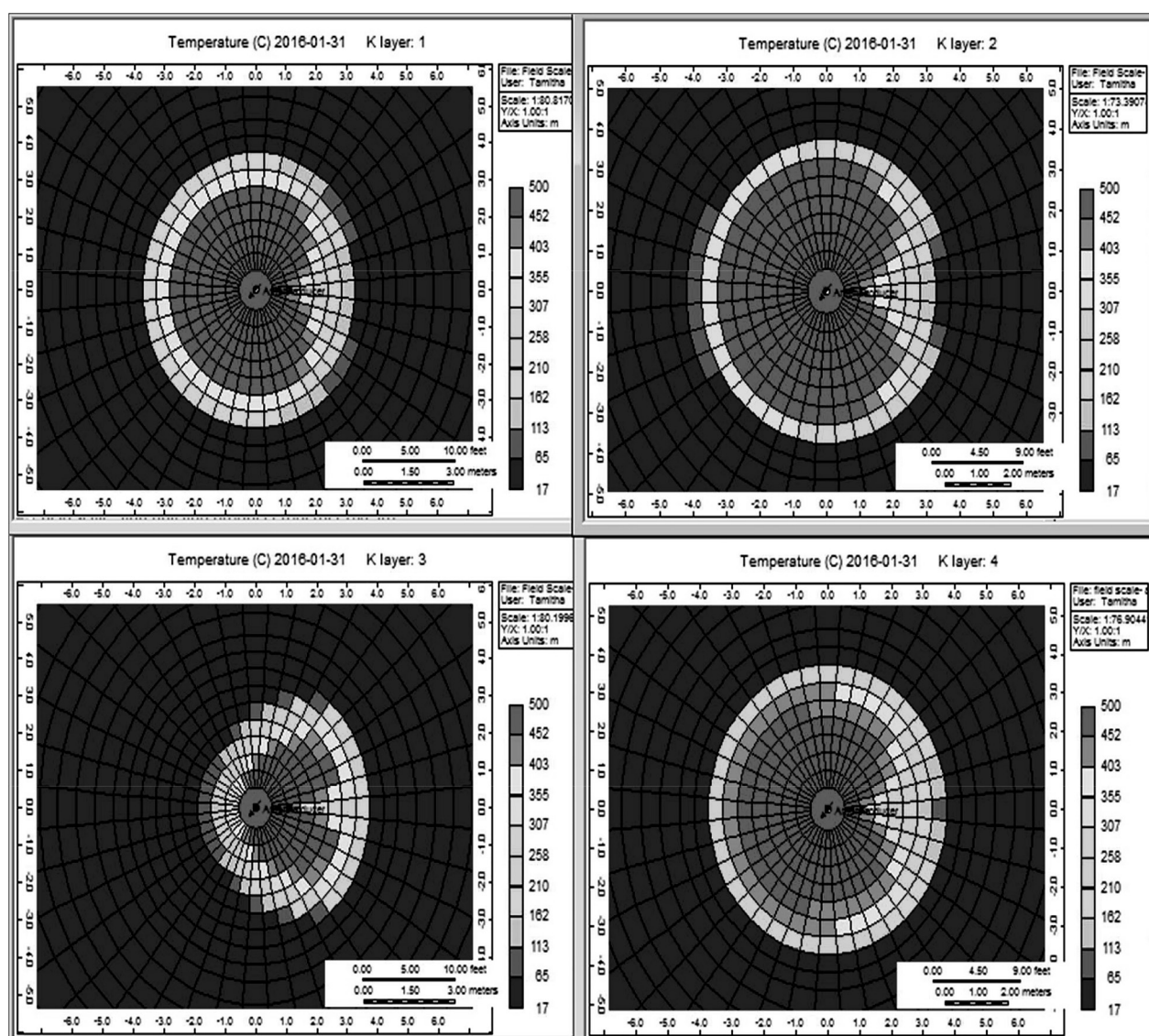


Figure 25: Areal maps of the four layers of the field (magnified) showing temperature variations that occur in each layer with RFH after 60 days. RFH is applied at the centre of the field via an antenna well. The colour variation depict temperature variations based on the scale at the side of the map which goes from 17 to 500 °C.

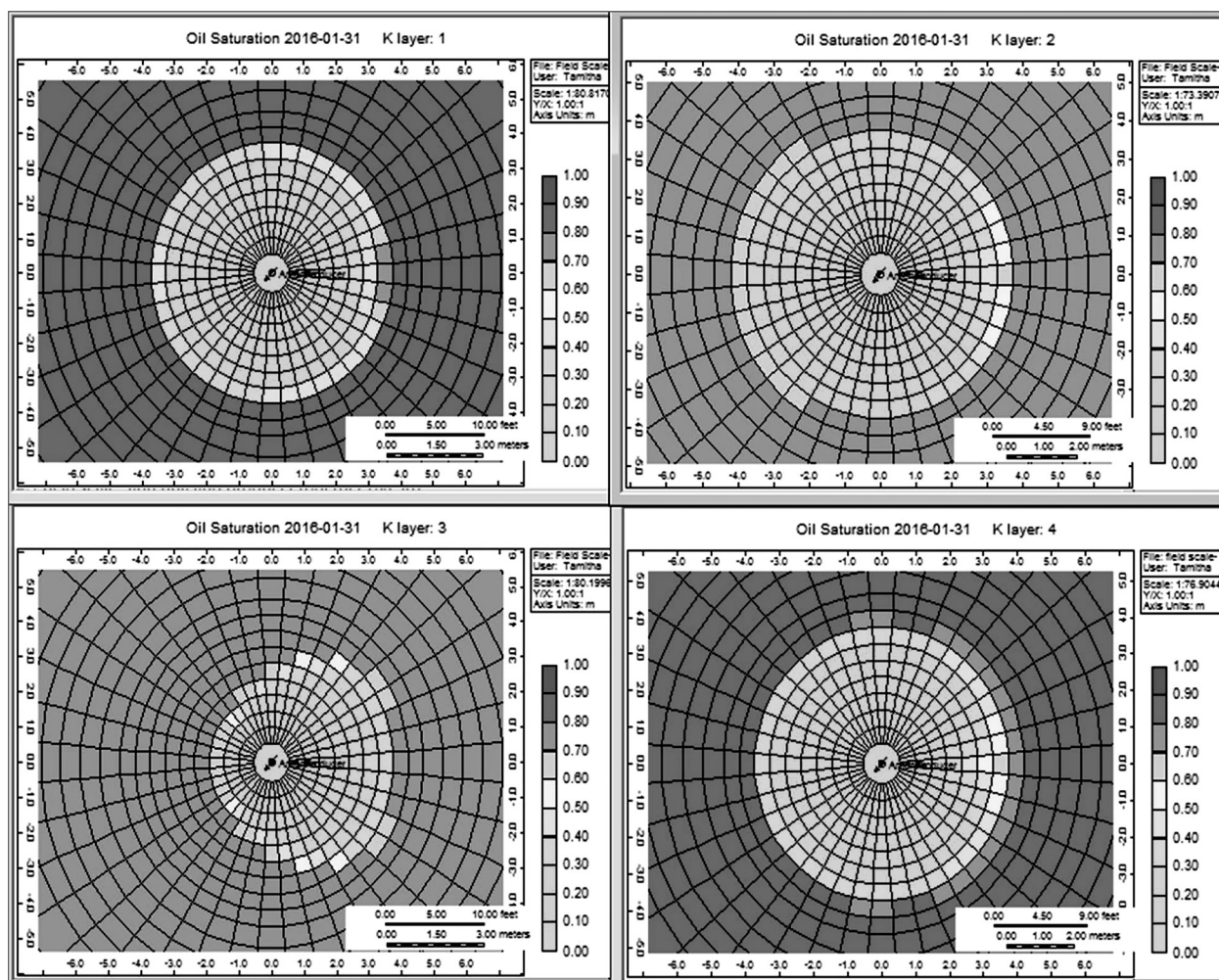


Figure 26: Areal maps of the four layers of the field (magnified) showing oil saturation variations that occur in each layer with RFH after 60 days. The field is depleted during RFH via a production well at the centre of the field. The colour variation depict oil saturation variations based on the scale at the side of the map which goes from 0% to 100% oil saturation.

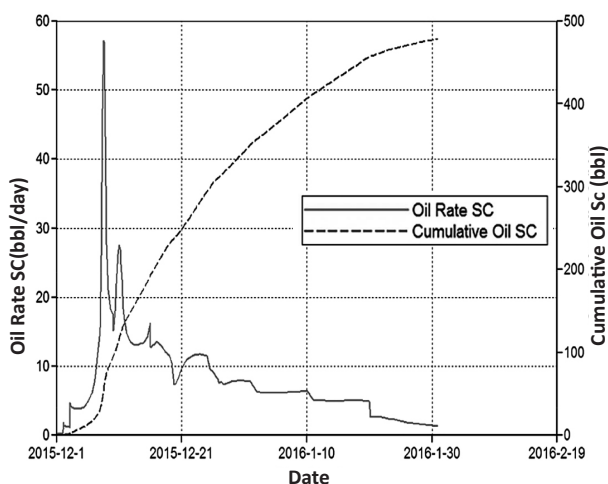


Figure 27: Oil rate and cumulated oil production versus time for the application of RFH to a field with a single vertical well.

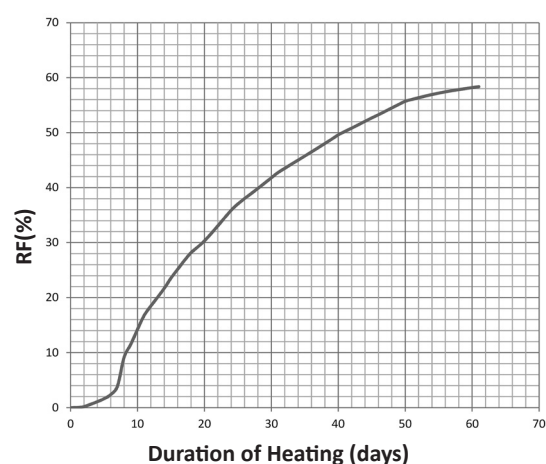


Figure 28: Recovery factor versus time for the application of RFH to a field with a single vertical well.

Figure 29 shows the variation of temperature versus distance from the centrally located antenna and that of oil saturation versus distance. The plots indicate that heating extended to approximately 4 meters away from the antenna, but oil has depleted to a distance of 3.5 m.

Horizontal Well Orientation

Horizontal wells were placed in each layer of the reservoir and extended to the end of the section being modeled (Figure 30). The plots (Figure 31) show that after 60 days, heating extends further out than in the case with a single vertical production well even though the same vertical antenna is

being used. This indicates that as the sample is being heated, and oil is being removed, the sample is becoming more and more desiccated, and the zone of heating is growing as the desiccation zone grows, thereby recovering more oil.

Production was then extended for a year to observe the depletion via the horizontal wells with RFH. It was found that after a year, the saturation around the horizontal wells decreased significantly (Figure 32). However, Figure 33 shows that the recovery factor is not still plateaued. This indicated that production can continue since the oil production rates are still fairly high.

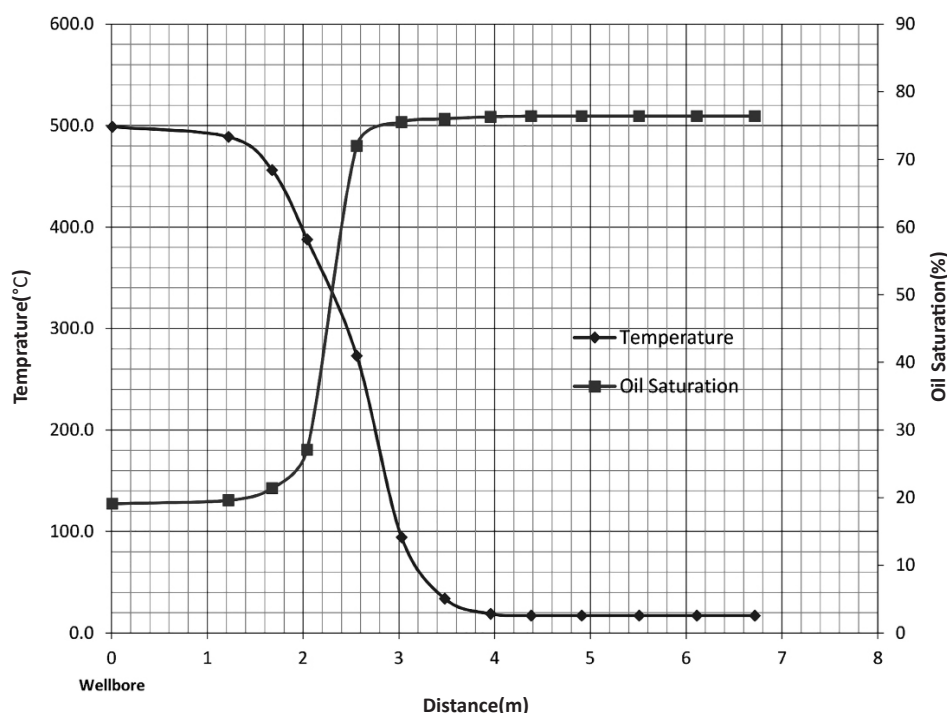


Figure 29: Temperature and oil saturation versus distance for a single central antenna and vertical producer.

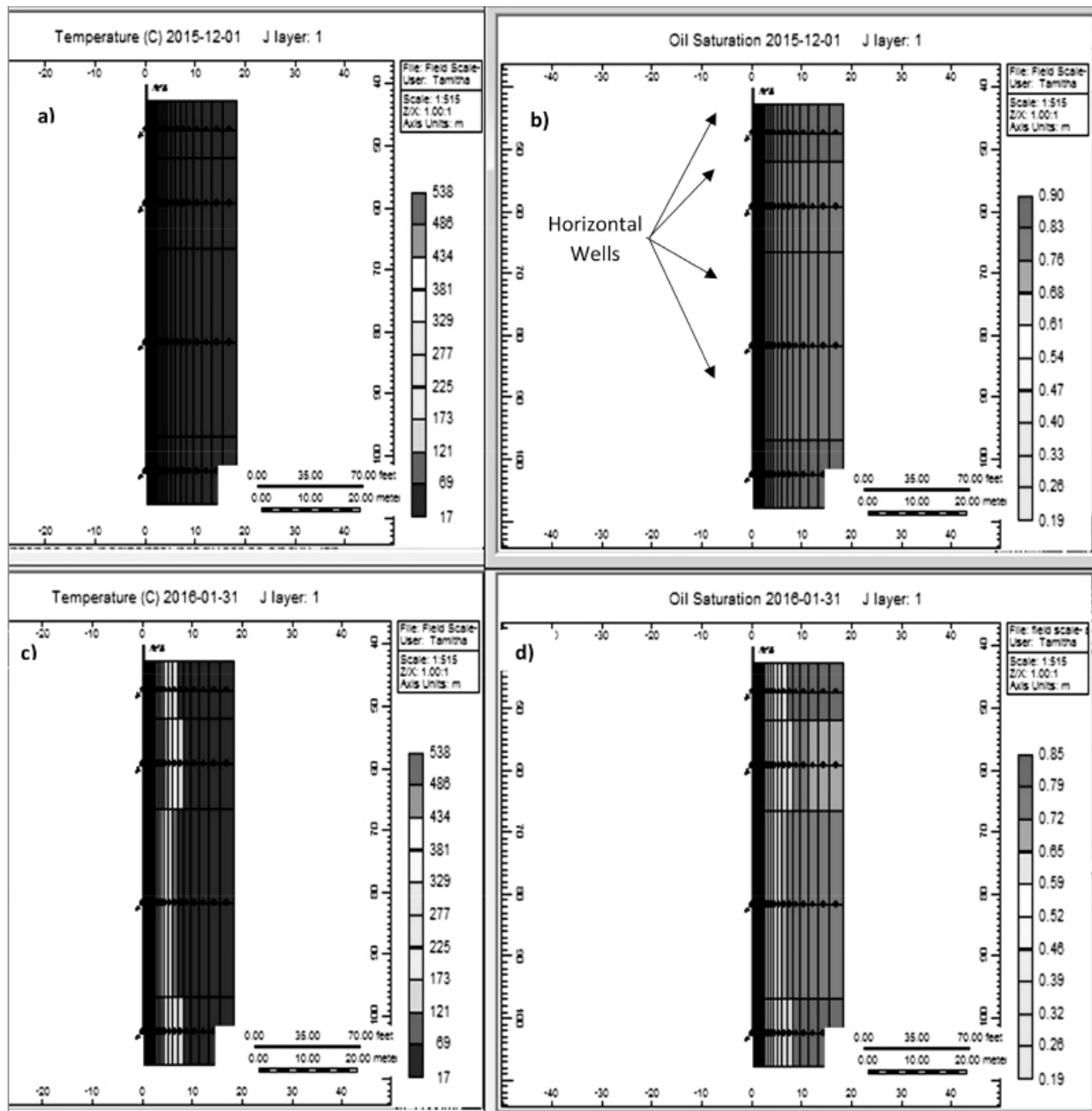


Figure 30:

- a) Cross sectional view of the field showing the placement of horizontal wells in each four layers and the initial temperature in the layers.
- b): Cross sectional view of the field showing the placement of horizontal wells in each four layers and the initial oil saturation in the layers.
- c) Resultant temperature variations from applying RFH via the horizontal wells to the field for 2 months.
- d) Resultant oil saturation variations from applying RFH and producing the field via the horizontal wells for 2 months.

* Colour variation scales at the side of each map depict either temperature or oil saturation amounts.

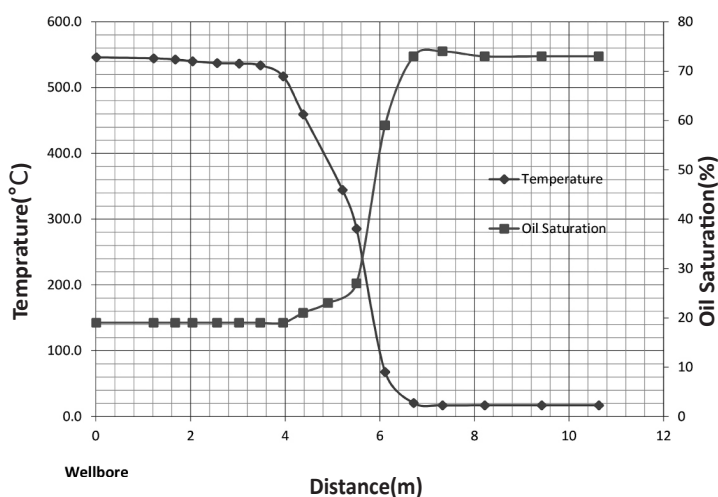


Figure 31: Temperature and oil saturation versus distance for a single antenna with a horizontal producer in each layer of the reservoir.

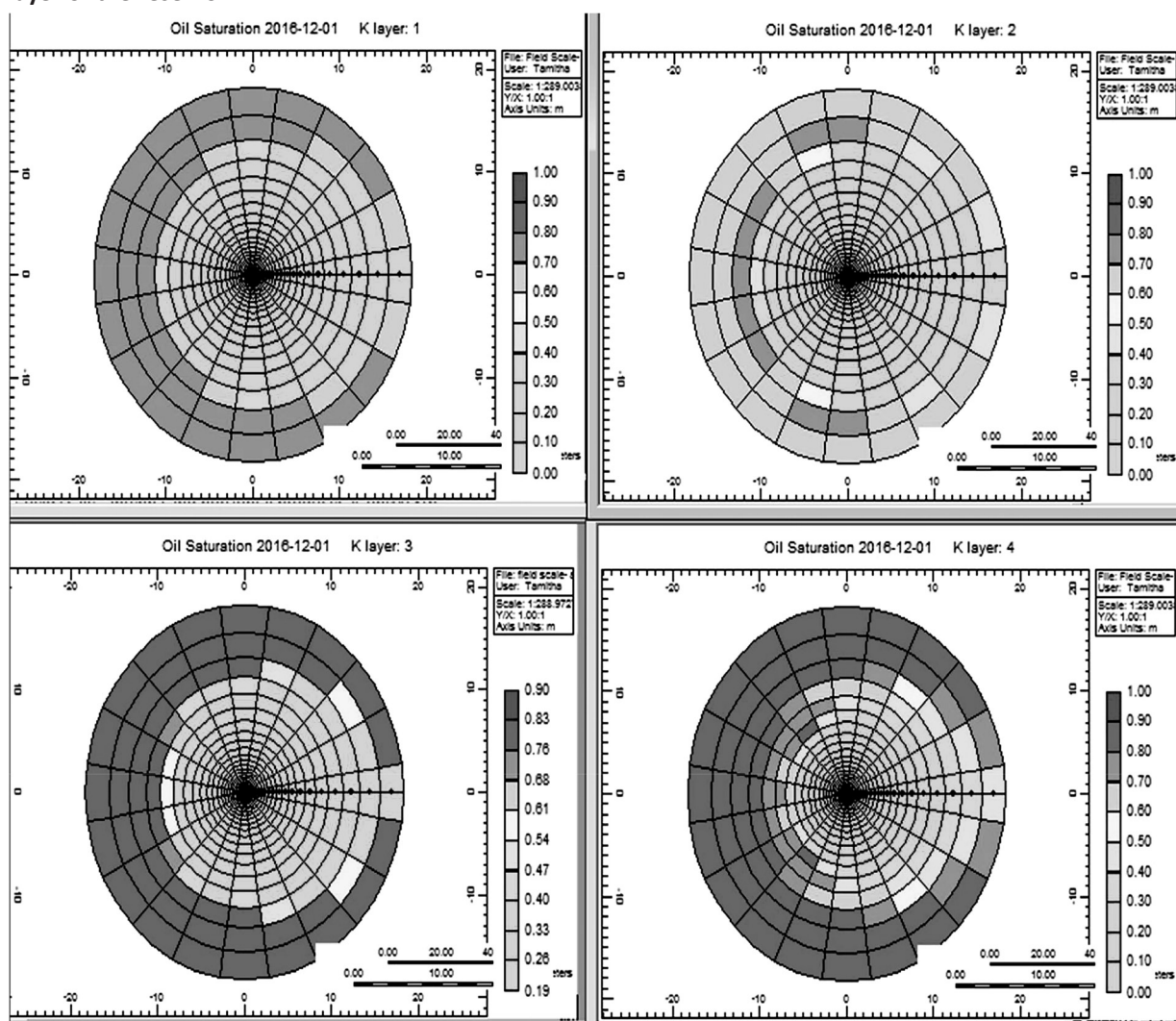


Figure 32: Areal maps of the four layers of the field showing oil saturation variations that occur in each layer with RFH after 1 year. In this case, the field is heated and depleted during RFH via horizontal wells. The colour variation depict oil saturation variations based on the scale at the side of the map which goes from 0% to 100% oil saturation.

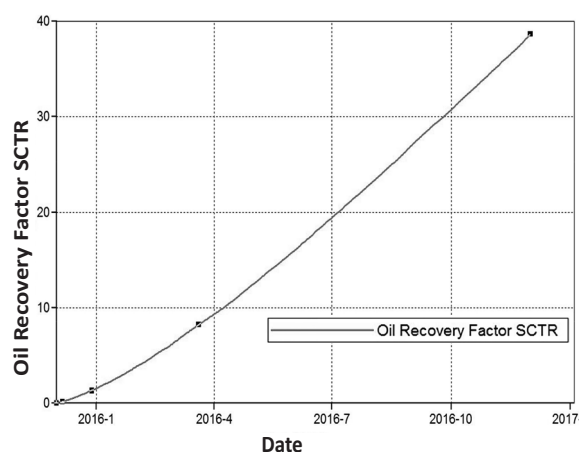


Figure 33: Recovery factor from the horizontal wells and RFH after 1 year

The viscosity data shown in Table 10 describe the changes in the viscosity of bitumen extracted from Trinidad oil sand, as temperature is increased [17]. It is expected that at temperatures above 200 °F, the bitumen will separate from the oil sand and flow toward the producer. Figure 34 shows the average reservoir temperature and an estimate of the average oil viscosity for this field over a period of one year. Viscosity estimates were made based on the data in Table 10.

Table 10: Oil viscosity measurements for the Trinidad oil sand of Trinidad [17].

Temperature	Viscosity
°C	(cP)
26.7	15,950
37.8	5,397
48.9	2,420
56.6	537
82.2	200
93.3	107

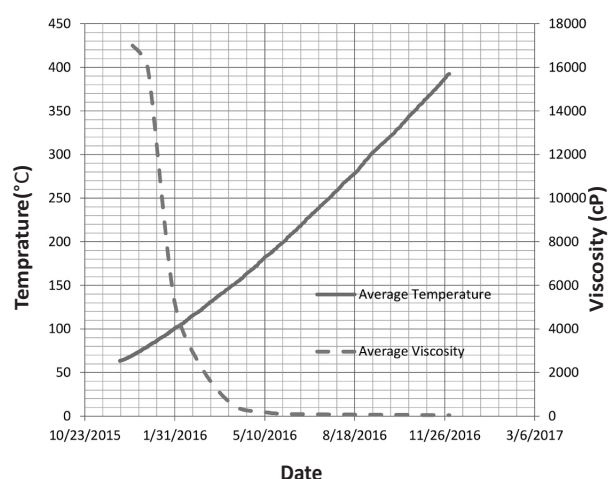


Figure 34: Average reservoir temperature and viscosity versus time.

CONCLUSIONS

1. The COMSOL Multiphysics RFH lab scale model showed that the temperatures of up to 500 °C could be reached safely by heating the oil sand within a copper chamber for 24 hours.
2. The up-scaled COMSOL Model created to match the simulation against experimental data showed that there was a good match. At 6.78 MHz, the temperature was increased to 130 °C after 30 days, and heating was extended radially up to 4 meters, which was similar to the actual mine face test conducted in Alberta [5].
3. The field scale COMSOL model which was based on Trinidad oil sand was used to determine that 11.5 kW of power was sufficient to provide electromagnetic energy to the field.
4. By applying RFH with a vertical antenna to all four layers of the simulated section of the oil sand reservoir in CMG STARS, a recovery factor of 58% was achieved in a period of 60 days for a distance of 3.5 meters away from the well bore. This was very optimistic case since the model was simple, and the four layers forming the oil sand field were

homogeneous throughout.

5. The addition of horizontal wells and antennas shows high recoveries of up to 40% after 1 year for the entire field. Horizontal wells, though more costly, will ultimately provide better heating and production.

6. The energy cost required to produce one barrel of oil by RFH was found to be USD 2.50

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NOMENCLATURES

EM	: Electromagnetics
RF	: Radio Frequency
RFH	: Radio-frequency Heating

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