The Application of Radio Frequency Heating Technology for Heavy Oil and Oil Sands Production

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1.0 Introduction

The viscosity of heavy oil and bituminous oil sands is so high that it renders conventional production impossible at original reservoir conditions. There are several ways of reducing the oil viscosity, but the most popular and effective involves injection of heat into the reservoir, most often using steam. It is well known that viscosity reduction follows an exponential trend versus the temperature. For example, a viscosity of 1,000,000 cp at 10°C reduces to 10 cp at 250°C. The typical behaviour of Athabasca bitumen is shown in Figure 1.

![Athabasca Viscosity vs. Temperature](image)

Figure 1. Typical behavior of the viscosity of Athabasca bitumen

The oil industry has been applying steam injection in three basic ways:

1. In a cyclic way known as Cyclic Steam Stimulation (CSS);
2. in a continuous way known as Steam Flooding (SF); and
3. using a process known as Steam Assisted Gravity Drainage (SAGD).

Diagrams illustrating how these three processes are applied in the field are shown in Figures 2, 3 and 4. The CSS and SF processes can be applied through both vertical and horizontal wells, while the SAGD process is only applied through horizontal wells.
Figure 2. Cyclic Steam Simulation

Figure 3. Steam Flood
These three processes have proven to be very effective when applied to the right reservoirs and under right conditions. There are however many circumstances where they simply cannot be applied, such as thin or shallow reservoirs, reservoirs with poor cap rock, fractured reservoirs, and high water saturation reservoirs, to name just a few. Additionally, steam injection processes are being increasingly criticized for low energy efficiency, high fresh water consumption and high CO₂ emissions (estimated to be responsible for 5% of Canadian CO₂ emissions).

Other thermal processes, such as hot water injection or in situ combustion have also been tested and applied. In the case of hot water injection, the oil/water mobility ratio is more favourable in the heated zone, compared to cold water injection, but at the water front, where the oil is still at reservoir temperature, the mobility ratio remains unfavourable, ultimately making this process unattractive (Prats, 1987). In the case of in situ combustion, while it seems to be effective from the reservoir behaviour point of view, the difficulties in its practical implementation, including the danger inherent in managing very high temperatures in the reservoir, have made it seldom a method of choice.

To overcome the inconveniences of steam injection and go beyond the other tested processes, oil companies are targeting some modifications to all these processes and exploring other alternative heating processes, two of the most promising being electric heating and radio frequency (RF) heating.

Of particular interest for down-hole heating of oil reservoirs is RF heating. This technology uses electromagnetic (EM) energy in the radio frequency spectrum for heating heavy oil and reducing its viscosity. Although the technology has been considered since the 1970s, it has not met with commercial success. This is mainly because the field tests were only partially successful, inconclusive or aborted due to failure. There were many factors contributing to this, including a high level of technological
difficulties, high cost and a poor understanding of the underlying process. However the fundamental scientific premises of the technology are sound and relatively simple, and were confirmed by basic experiments performed in the past, especially in Russia, USA and Canada, as summarized in a recent article (A. Mukhametshina and E. Martynova, 2013). While the experiments were encouraging, the overall complexity of the reservoir response to RF heating was not well understood, the simulation tools were not advanced enough to offer insights about the reservoir dynamics, and the complexity of the equipment required was overwhelming. For these reasons, the development of the technology was abandoned.

Progressive depletion of conventional oil reservoirs, high oil prices and the environmental and exploitation challenges mentioned above, provided impetus for renewed interest in RF heating as an alternative exploitation technology. Recent increases in computer power and significant advancements in modeling tools coupled with a deeper understanding of the technology itself have brought RF heating technology much closer to commercial viability. Several projects are currently underway the best known being the ESEIEH consortium, formed by Suncor Energy, Nexen, Harris Corporation and Devon Energy (and initially by Laricina Energy - now no longer in the project). According to press releases, this consortium has completed the first of several planned experiments, with encouraging enough results to proceed with the second phase of the project planned for the fall of 2014.

Some of the advantages of RF heating technology over traditional steam injection include:

- RF heating can be applied equally well in deep, shallow, thin and thick reservoirs, since the EM field does not require any hard cap rock for containment.
- Initial low permeability of the heavy oil formation does not limit the amount of RF power which can be injected.
- The technology can be applied effectively in heterogeneous reservoirs with high permeability streaks or fractures, as they do not cause the EM field to leak.
- RF heating significantly reduces the amount of water used in the process, compared to steam injection.
- Preliminary energy balance calculations indicate that RF heating is economically attractive and suggest that it could potentially replace the SAGD process in a foreseeable future, resulting in important reductions in both fresh water use and CO₂ emissions.
- The technology can be an all-electric process, powered by green sources of electricity.
2.0 Electromagnetic Heating Methods

An EM heating process involves using EM energy to heat heavy oil reservoirs. There different types of EM heating are described below:

- Electrical heaters
- Low frequency electric resistive heating
- RF heating

2.1 Electrical Heater

One way of applying electromagnetic energy to a heavy oil formation is by using an array of down-hole electrical resistance heaters. The heaters can be installed in vertical or horizontal wells and are in direct contact with the formation. As electrical current propagates through a heater its temperature increases dramatically, and the heat penetrates into the formation via thermal conduction.

Two of the main advantages of this technique are its relative simplicity and its low cost of deployment. However, its disadvantage lies in the fact that it relies on thermal conduction, which can be very low in heavy oil reservoirs. Therefore, the heating process is slow and only very limited amounts of energy can be injected by a single well; otherwise, potentially well-destroying hot spots can be created.

An example of this technology is Thermal Assisted Gravity Drainage (TAGD) technology pioneered by Athabasca Oil Corporation. Field production tests have been performed by Athabasca at its Dover West site in 2012 and 2013 and encouraging results were obtained (reference: http://www.atha.com/operations/technology/tagd.html).

2.2 Electric Resistive Heating

The Electric Resistive Heating (ERH) process uses 50-60 Hz AC current which flows through the reservoir converting electrical energy to heat (resistive heating). The basic configurations of the ERH system are shown in Figure 5. The technology can be applied to vertical or horizontal wells. Typically, two electrodes are inserted into wells at relatively close distance between them. The electrodes are insulated from the soil in all regions except the oil bearing reservoir which needs to be heated. The electrodes are connected to an AC source located at the surface. Due to the presence of brine in the formation, its electrical conductivity is high. Therefore, the current flow is established through the reservoir between the electrodes and the electrical energy is converted to heat in an ohmic process.

Unfortunately, the temperature profile of the heated formation is very non-uniform, with the highest temperature being next to the electrodes and lowest in the area between them. The high temperature areas are dangerous for the process because they can cause well destruction or cause water evaporation, introducing a layer of poor conductivity and shutting down the current flow. Therefore, special techniques need to be applied to avoid creation of high temperature areas.

The ERH system in its basic form is relatively simple to design and has a lower implementation cost. However, it typically requires relatively small distance between the electrodes, necessitating such a high number and density of wells that the project economics are jeopardized. Another disadvantage of this
technology is the creation of high temperature areas or hot spots, which are not only dangerous for the wells' structural integrity, but also cause premature heating shutdown.

![Diagram](image-url)  

**Figure 5. Basic electric resistive model**

### 2.3 Radio Frequency Heating

Published literature related to EM heating (A. Mukhametshina, et al. 2013; I. Bogdanov, et al. 2011; B. Wacker, et al. 2011; M. Koolman, et al. 2008; M.A. Carrizales, et al. 2008; C. Ovalles, et al. 2002; A. D. Hiebert, et al. 1989; R.G. McPherson, et al. 1985) and in-house life cycle analysis of RF heating indicate that this technology has the potential to become an economically successful process for thermal recovery of heavy oil. RF heating technology, in its basic form, operates through down-hole deployment of an antenna or applicator which radiates an EM field into an oil-bearing formation (see a typical dipole in Figure 6). A heavy oil reservoir is electromagnetically lossy, mainly due to polarization effects in water or brine present in the formation. Therefore, the energy of the EM wave is dissipated into heat, resulting in the increased temperature of fluids and rocks. The oil is heated by an indirect process: the water present in the reservoir is heated and that heat is transmitted to the heavy oil, reducing its viscosity and enabling commercial production. Typically, EM frequencies between 10 kHz and 100 MHz are used for this type of application. These frequencies belong to the radio frequency (RF) range, thus term RF heating is often used.

RF heating works at reservoir conditions because the water, present in all oil reservoirs, can be heated by the EM energy generated by the antenna. The water is called a lossy medium, while rock, oil and gases, including water steam, are considered lossless or very low loss media. As the power of the EM field decreases faster than $1/r^2$ with the distance from the antenna, most of the heat, especially at the beginning of the process, goes to the water surrounding the antenna well. As time passes and this water is converted into steam, causing the EM waves to penetrate deeper into the reservoir, “looking” for the lossy medium, and additional reservoir volume is contacted and heated.
The desiccated volume (the steam zone) is considered low loss, therefore no heat (or much smaller quantities of it) goes to this region. This fact makes the mechanism a quasi-auto regulated process. The area with high water saturation ($S_w$) near the antenna is heated first. Once the temperature in this area reaches the steam saturation temperature and the water disappears, most of the heat goes to the next water-saturated region, significantly reducing the amount of heat going to the desiccated volume. This auto-regulation is one of the most relevant differences between this process and the heating process performed by a heater (electrical heating) or an ERH system.

Schematics on how to apply this technology in the field, mimicking the three ways of steam injection, are shown in Figures 7, 8 and 9.
Figure 7. Cyclic RF heating process

Figure 8. RF Flood - Continuous RF heating process in a vertical design
3.0 Modeling of the RF Heating Process

The EM field pattern is governed mostly by the radiated RF power, antenna size and type, EM properties of the formation and the materials used inside the well. The most important EM reservoir properties are electric permittivity and conductivity. Typically, the formation components are considered to be non-magnetic. However, if some magnetic materials are present their magnetic permeability and conductivity can be important too.

The EM properties of the formation are typically obtained through measurements and/or by using theoretical models, such as Archie's law, Wax-Smiths formula, polarization of mixtures etc. Brine is the component which most strongly affects the EM properties of the formation. As the heating process progresses, the temperature of the formation and the water saturation change, changing the properties of the formation and consequently the EM field pattern. As an example, dependence of the dielectric permittivity and conductivity on water saturation and temperature in a typical oil sands reservoir in northern Alberta is shown in Table 1 (properties derived from A.D. Hiebert et al., JCPT 1989).

RF heating is a dynamic process where the energy carried by the radiated EM wave is used to heat a heavy oil bearing formation. During the heating process, the reservoir's petrophysical properties (water saturation, porosity, permeability, etc.), conditions (pressure, temperature, etc.), and EM properties are constantly changing, affecting the EM field and the heating pattern itself. Therefore, to accurately model the RF heating process, a combination of EM, thermal, and reservoir simulators is required.
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<thead>
<tr>
<th>Temperature (°C)</th>
<th>Water Saturation ($S_w$)</th>
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<tbody>
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<tr>
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<tr>
<td>30</td>
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<td>50</td>
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<td>3.665</td>
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<tr>
<td>300</td>
<td>4.015</td>
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Table 1. Relative Electric Permittivity ($\varepsilon_r$) as a Function of Temperature and Water Saturation

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Water Saturation ($S_w$)</th>
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Table 2. Electric Conductivity ($\sigma$ in Siemens/meter (S/m)) as a Function of Temperature and Water Saturation

3.1 Theoretical Model

The EM solver calculates the EM field in the reservoir taking into account geometries of the antenna, well and the formation features, as well as the EM properties of the materials involved. The field is obtained by solving Maxwell’s equations in the discretized computational domain. Time-domain Maxwell’s curl equations for isotropic materials are given below:

\[
\nabla \times \vec{H} = \varepsilon_0 \varepsilon_r \frac{\partial \vec{E}}{\partial t} + \sigma \vec{E} \\
\n\nabla \times \vec{E} = -\mu_0 \mu_r \frac{\partial \vec{H}}{\partial t} + \sigma^* \vec{H}
\]

where $\vec{E}$ and $\vec{H}$ are the electric and magnetic field vectors, $\mu_0$ and $\varepsilon_0$ are the permeability and permittivity of vacuum, $\mu_r$ and $\varepsilon_r$ are the relative permeability and permittivity of the materials used,
while $\sigma$ and $\sigma^*$ are the electrical and magnetic conductivities. If the materials are anisotropic, the scalars $\varepsilon_r$, $\mu_r$, $\sigma$, and $\sigma^*$ turn into tensors.

The thermal process is governed by the Pennes heat equation given below:

$$\rho c \frac{\partial T}{\partial t} + \rho f c_f \vec{v}_f \cdot \nabla T = \nabla \cdot (k \nabla T) + \dot{Q}$$  \hspace{1cm} (2)

where $\rho$, $c$, and $k$ are the density, specific heat capacity and thermal conductivity of the medium, $\rho_f$, $c_f$, and $k_f$ are the density, specific heat capacity and $\dot{Q}$ is the heat generation rate per unit volume. In the RF heating process, the heat generation rate is equal to the EM power density, i.e.

$$\dot{Q} = P = \sigma |E|^2$$  \hspace{1cm} (3)

The fluid flow in the oil reservoir is described by the mass conservation equation combined with the momentum equation (Darcy's law) for each fluid phase $i$ (water, oil, gas) and is written as:

$$-\nabla \cdot \vec{v}_i - \frac{q_i}{\rho} = \frac{\partial}{\partial t} \left( \phi \frac{S_i}{B_i} \right)$$  \hspace{1cm} (4)

where $v_i$ is velocity, $B_i$ is the formation volume factor, $q_i$ is the production/injection, $\rho$ is the density, $\phi$ is the porosity and $S_i$ is the saturation.

The generalized Darcy's law is included in the velocity variable $V_i$ and can be expressed as:

$$V_i = -\frac{K_i \partial \Phi}{\mu_i \partial j}$$  \hspace{1cm} (5)

where $K_i$ is permeability, $\mu_i$ is viscosity, $\Phi$ is the potential (pressure plus gravity), and $j$ is the direction ($x$, $y$ or $z$).

### 3.2 Numerical Model

In order to rigorously describe the RF heating process, equations (1)-(5) need to be solved in an implicit manner. However, currently no software tools are available to accomplish this task. The usual way to simulate the phenomenon in a reasonably accurate way is by iterating between solving the Maxwell equations (the EM simulator) and solving the heat, mass conservation and Darcy equations (the reservoir simulator). The approach is reasonable, as the time scales of fluid/thermal processes and EM processes are vastly different, such that the EM simulator can consider the reservoir as static at its time scale (nanoseconds).

Although some multi-physics solvers are available in the market, they are mostly developed as general purpose software and lack the specialization and sophistication of dedicated reservoir simulators.

Recognizing the need for advanced and comprehensive simulation tools capable of simulating an RF heating process, Acceleware has developed a software application, AxHeat™, which integrates reservoir simulation with Acceleware’s EM simulator to accurately model the heating process.
AxHeat works in the following way:

1. As input data, AxHeat requires a typical reservoir model describing the reservoir condition and its petrophysical properties, as well as a set of temperature dependent EM property tables (Table 1 and Table 2) for the formation and well materials. The time period which needs to be simulated is divided into time-steps defined by the user.

2. At the beginning of each time-step, the reservoir simulator outputs water saturation and temperature in each cell and well component. Based on this information, AxHeat calculates the EM properties of the reservoir and well components. These values are then interpolated to the grid used by the EM simulator. The interpolation algorithm needs to be able to properly treat the transitions between different reservoir cells, otherwise non-physical numerical reflections in the EM simulation may occur.

3. The EM simulator calculates the EM field radiated by the antenna into the formation.

4. Once a new EM field is available, AxHeat calculates the heat generation rate going into each reservoir simulator cell and well component. This algorithm needs to make sure that there is no power leakage between neighboring reservoir cells, otherwise artificial overheating of certain formation regions may be seen in the simulation process.

5. The heat generation rate is fed to the reservoir simulator, which continues running for the next time-step interval, calculating new values of water saturation, temperature, and other petrophysical formation parameters.

6. Steps 2-5 are repeated until the end of the simulation time is reached.

The block diagram of the AxHeat algorithm is shown in Figure 10.

Figure 10. Schematic showing how AxHeat works
4.0 Radio Frequency Heating Use Case Simulations

The following are some examples that illustrate the results that can be obtained using AxHeat as part of a RF heating solution.

4.1 Heat and Temperature Distribution with a Vertical Antenna

In this example we use the properties of a generic carbonate reservoir of Alberta. The reservoir is 55m thick, with 15°C initial temperature, approximately 1000 kPa initial pressure and 5,000,000 cp initial bitumen viscosity. The initial reservoir properties are constant horizontally, but change vertically. The antenna is a conventional dipole, as shown in Figure 11, and the power and frequency applied were 110 kW (2kW/m of antenna) and 1 MHz. Figure 11 also shows a 3D view of the simulation model.

Figure 11. The dipole and a 3D view of the simulation model

Figure 12 shows a cross section of the heat distribution produced by the EM field after one year. It can be seen that while most of the heat goes to the cells adjacent to the antenna, the border cells are also receiving part of the heat generated. This means that the temperature starts increasing all through the reservoir from the beginning of the heating process. The areas closest to the antenna obviously heat up faster than areas further away from it. The scale of Figure 12 is logarithmic to better appreciate the small variations. The white cells close to the antenna show that these cells are receiving less than 50 J/d, the minimum value in the logarithmic scale. The reason is that in these cells the water saturation is already zero (there is steam there) and they are not receiving the heat they were receiving while they still had some liquid water.

Figure 13 shows the temperature distribution after one year of heating, also in a logarithmic scale. It can be seen that, after one year, the temperature has increased approximately 4-5 °C at a distance of 15m. The temperature close to the antenna is around 180 °C, which is the steam saturation temperature at the current reservoir pressure. As mentioned above, the maximum temperature expected in the reservoir will be the steam saturation temperature at the reservoir pressure, because once the steam is

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Figure 12 and Figure 13.
generated, the medium becomes less lossy, receiving only the heat necessary to keep the water in the steam phase.

The behavior when the RF heating process is applied to a horizontal antenna is very similar.

![Figure 12. Cross section showing the heat distribution after one year of heating](image1)

![Figure 13. Temperature distribution after one year of heating](image2)
4.2 Production with a Vertical Antenna

In the second example we use properties of a generic heavy oil reservoir with $S_w = 0.5$. Here we simulate oil production in an approximate 7-spot array symmetry element configuration with a spacing of 70 feet (21m) between wells (see Figure 14). Two scenarios are considered: in the first we simulate the production by natural depletion, without any heating or injection process. In the second, we simulate production with RF heating plus gas injection through the central well. The gas is necessary to create an appropriate drawdown in the producing wells, as the heating process on its own is not able to pressurize the reservoir enough to produce at economic rates.

Gas injection in vertical wells is not usually effective if the oil viscosity is extremely high, as is the case of Alberta bitumen. As a production example where the oil is extremely viscous, RF heating and gas injection are recommended to be applied through horizontal wells. For this configuration, the gas injection, similar to steam injection, takes advantage of the effect of gravity resulting in a very effective process.

The comparison between the two scenarios, shown in Figure 15, clearly shows that the first scenario does not yield any commercial oil rates, while the second one, when applying the RF heating process plus some gas injection, offers reasonably good oil rates, even without optimization. It must be remembered that in a 7-spot pattern only 1/3 of the producing wells are simulated, therefore the real oil rate has to be multiplied by three. In the Figure 15, the production rate of a generic well, WPROD3, is plotted. Also, while the recovery factor in the first scenario is less than 1%, in the second scenario it is approximately 30% after one hundred days of heating and producing, and approximately 50% after one year.

Figure 14. Schematic of the grid used in the second example (top view)
Figure 15. Oil rate of simulated well WPROD3 and recovery factor for no heating and RF heating cases

Figure 16 shows an energy balance plot showing how much energy was injected through the RF heating process (without considering the energy injected by the gas injection) to produce one cubic meter of oil. It can be seen that the instantaneous energy/oil ratio is below 1 GJ/m³ (gigajoules per cubic meter) during the first three months, going up to 2.5 GJ/m³ after one year. In a typical SAGD project the energy/oil ratio is about 9 GJ/m³ (be aware that SAGD works with horizontal wells, while the current example works with vertical wells).

Figure 16. Energy/Oil ratio for the case of RF heating
4.3 Production with a Horizontal Antenna

In the third example we also use a reservoir with properties typical of the Alberta oil sands. In this case the antenna is located horizontally in a similar way to a typical SAGD process. The producer is at the bottom of the reservoir and the antenna is 5m above, in the injection well. For demonstration purposes, the antenna is only 50m long, but the results can easily be linearly extrapolated to estimate the oil production of a typical 800m long well. The spacing is 80m, but smaller spacing could be taken and less power could be needed to deplete the reservoir. Ultimately the economic analysis will be the factor dictating the best option in each case. In this example natural gas is injected through the antenna well for pressure support. The injection of a fluid for pressure support can be useful or even necessary in some cases to have economic oil production rates. Figure 17 shows a 3D view of the symmetry element used in the simulation (half of the model), and also depicts the well pair.

The technology of RF heating with gas injection appears to work well even in very viscous oil reservoirs when applied with horizontal antennas, because gravity will help to send the gas to the top and push the oil to the producing bottom well, just as it happens in a SAGD process.

Figure 18 shows the oil saturation at four different moments. It can be seen that the oil is drained in a very similar manner as in a SAG process. Figure 19 shows the heat distribution, in logarithmic scale, produced by the radiating antenna. Figure 20 shows the temperature distribution, again in logarithmic scale to better observe the variations in the lowest side of the scale.

![Figure 17. A 3D view of half of the model showing the location of the two wells (the antenna is placed in the top well)](image-url)
Figure 18. Cross section view of oil saturation: Initial, and after 2, 3 and 5 years
Figure 19. Cross section view of heat distribution: Initial, and after 2, 3 and 5 years
Figure 21 shows the oil production performance. Again, the oil rate behaviour looks very similar to a SAGD process, with a ramp up stage, a plateau stage and a declining stage. It has to be remembered that the oil rate corresponds to a 50m long well. Note that the recovery factor is also similar to that from a SAGD process. This example uses a simplified, homogeneous reservoir model; actual results may differ with real world heterogeneous reservoirs.
Finally, Figure 22 shows the energy balance of the process. It can be seen that the instantaneous energy rate necessary to produce a cubic meter of bitumen during the plateau stage is approximately 2.5 GJ/day, while the cumulative energy needed after 10 years of production is around 3 GJ/day. A typical SAGD process uses approximately 9 GJ/day, so, from the energy balance point of view, the RF heating process appears to be very attractive. Of course a rigorous economic analysis is needed to confirm the benefits of the process and this will be shown in section 5.
4.4 A Comparison between Radio Frequency Heating and an Electrical Heater

As it was mentioned above, electrical heating is simpler than RF heating and some engineers could wonder why not to apply it instead of a more complicated and expensive RF heating process. The simulation study, detailed below, provides additional insight into the significant differences between the two processes. In this example a comparison is presented between the results obtained with a heater and with an antenna, both placed in identical vertical wells with the same characteristics.

In both cases the length of the heater and the antenna was the same (50 m), and the same power was applied (100 kW). The comparison was made with the same reservoir model used in first example above. In the case of the antenna, a cooling fluid was circulated through the tubing and annulus to protect the well and antenna materials. No cooling process was applied to the heater, as the cooling process would kill the heating efficiency. This simple observation also underlines the key difference between the approaches. RF heating is volumetric in the formation material: the heat is generated in the reservoir volume surrounding the antenna, while in a process with a heater the heat is entering the formation through a surface immediately next to the heater by conduction.

In the case of the heater, a maximum temperature of 250°C in the well and the immediate surrounding materials was enforced. This assumption represents correctly the real application of the technology and it is managed by turning off the power immediately once a point of the heater reaches the maximum temperature and turning it on again once the temperature of all the points is again below the limit. For practical reasons (simulation run time) the temperature check cannot be done at every time step, so it is done once per day. Note, a one day period is likely too long in some circumstances and it can happen that the temperature can continue rising for a while, even if it is already above the limit, or continue decreasing, even if it is below the limit. Nevertheless the example illustrates the mechanism at play in this case.

The same limitation is also necessary in the antenna, but in this case the control is much easier, because the process is self-regulated and the maximum temperature will be the steam saturation temperature, which depends on the reservoir pressure. For the present example, the steam saturation temperature is around 190°C. The antenna and well are also locally cooled though a circulating fluid to maintain their integrity.

The results obtained, after 500 days of operation, are shown in Figures 23 and 24. Figure 23 shows the difference in the heat distribution. In the RF/antenna case, the RF radiation generates the heat in the whole reservoir volume. The heat dissipation tends to be much stronger close to the antenna, and decays approximately proportional to $1/r^a$ (2 ≤ $a$ ≤ 3, depending on antenna type) close to the antenna and a combination of $1/r^2$ and an exponential function at larger distances. The heat pattern is changing in the volume with time, reflecting changes in material properties. In contrast, the heater generates the heat just in the heater, it is constant all the time, and penetrates into the reservoir mainly by thermal conduction.

After 500 days of operation, profound differences in the behavior of the systems can be observed. In the RF/antenna case, the heat generation close to the center of the antenna is low (the white color means
that the values fall below the lowest value of the scale). This is because by that time the water has evaporated and in doing so the mechanism for RF conversion to heat has been removed. Note that RF energy dissipation to heat relies on material with relatively high RF electrical conductivity, and typically in bitumen reservoirs the material with this property is water.

Figure 23. Heat distribution into the system: Left, antenna case; right, heater case

Figure 24 shows the temperature distributions also at 500 days. It can be seen that in the case of the heater the temperature is much more concentrated around the heater itself, while in the case of the antenna the temperature expands and penetrates in the reservoir much more efficiently.

Figure 24. Temperature distribution: Left, antenna case; right, heater case

Of course, because of the restriction in the maximum temperature in the heater, the total energy injected in both cases is different. The antenna can operate continuously, while the heater needs to be turned on and off during the process. This fact also speaks about the big difference in the applicability of both technologies.
To see the differences in the moment the same energy has been injected in both cases, Figure 25 shows the temperature distribution when a total of 1.44E12 Joules has been injected in both cases. The temperature distribution looks similar in both cases, however in the case of the antenna the heat has dispersed a little bit further into the formation. This similarity is mainly due to the fact that the time the antenna has been working is too short to show its full potential.

![Temperature distribution](image)

**Figure 25. Temperature distribution when 1.44 J have been injected: Left, antenna case; right, heater case**

The main difference between the heater case and the antenna case is the time required to inject the same amount of energy into the formation. While it takes 600 days for the heater to deliver 1.44E12 J under temperature control conditions, it takes only 84 days for the RF system. The relevance of this comparison is that, in the case of the heater, the operator has to solve the dilemma of injecting less heat to keep the integrity of the materials, and consequently having poor temperature distribution, or eliminating the temperature control to have better temperature distribution, and consequently risking damage to the materials and the well itself.
5.0 Preliminary Economic Analysis of Radio Frequency Heating

In this section a simple comparison between the economics of the RF heating process and other electrical and steam-based thermal recovery methods is presented. The analysis must be considered preliminary, because no real field projects have been implemented yet.

Effective steam oil ratio is a measure of the energy efficiency of an enhanced oil recovery technique. Steam oil ratio compares the amount of steam (in barrels of water equivalent) required to produce a barrel of oil. Effective steam oil ratio for non-steam methods is computed by calculating the input energy expressed as an equivalent barrels of steam quantity.

The benefits of the process from an energy balance point of view are presented below. Table 3 includes a comparative analysis between a few thermal processes. The data for the table was taken from Bogdanov et al., 2011, (courtesy of TOTAL S.A.) and shows a comparison of several in-situ oil sands production technologies according to theoretical efficiency. In the conceptual case described in the example 3, section 4.3. the effective steam to oil ratio was calculated to be 1.1, which compares quite favourably to the electrical and steam-based approaches listed below.

<table>
<thead>
<tr>
<th>Type of Heating</th>
<th>Effective Steam to Oil Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Frequency Heating</td>
<td>1.8-2.5</td>
</tr>
<tr>
<td>Conductive Heating</td>
<td>2.2</td>
</tr>
<tr>
<td>SAGD Heating</td>
<td>3.3</td>
</tr>
<tr>
<td>RF Heating (no pressure enhancement)</td>
<td>1.8-2.2</td>
</tr>
<tr>
<td>RF Heating (with pressure enhancement)</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Table 3. Steam to Oil ratio comparison for a few thermal processes
6.0 Conclusions

The following conclusions can be drawn from the study described in this paper:

- RF heating process appears to be sufficiently well understood to be developed into new heating technology and applied in field projects.
- RF heating technology seems to be particularly well suited to the production of otherwise stranded reserves, especially in cases where steam injection would be difficult to apply, such as in thin, shallow, no cap rock, and fractured or highly heterogeneous reservoirs.
- The performance of a typical heavy oil reservoir, when heated with the RF heating technology, seems to be very similar to the case when steam injection is applied.
- From the energy balance point of view, RF heating technology seems to have significant advantages when compared with other conventional heating processes, such as steam injection.
- From an economic point of view, RF heating also seems to have important advantages versus a typical SAGD process.
- From an environmental point of view, RF heating can be an all-electric process (fueled by renewable sources) that does not use external water and is more energy efficient than steam based methods.
- In many cases, RF heating technology will need to be applied together with another process for pressure support. Heating alone may not be sufficient to produce oil at commercial rates. For a design similar to a SAGD process, gas injection seems to work effectively and could be cheaper than other fluid injection.
- The main advantage of RF heating technology, as compared with other electrical heating processes, is that the RF process heats the reservoir volumetrically while the heater relies only on conduction to propagate heat through the reservoir.

For more information on Acceleware’s RF heating simulation software and engineering services please visit [www.acceleware.com](http://www.acceleware.com) or contact us at:

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7.0 References

12. CERI Report, May 2013