Chapter 44

RADIO-FREQUENCY HEATING TO RECOVER OIL FROM UTAH TAR SANDS

J. Bridges, G. Stresty, A. Taflove, and R. Snow

Abstract

The IITRI RF Process for tar sands consists of two steps: first, the deposit is volumetrically heated with radio frequency energy to lower the viscosity of the bitumen; and the second, the bitumen is produced by one of several petroleum recovery methods.

The RF (radio frequency) heating step is accomplished by inserting tubular electrodes into boreholes, and energizing them with an RF power source. The pattern of electrodes is designed so that the deposit between the electrodes is uniformly heated, with a minimum of energy loss. The RF is selected on the basis of the electromagnetic characteristics of the deposit. Electrical properties of Utah tar sands have been measured and found to behave as heterogeneous dielectrics, with parameters varying with moisture content.

To demonstrate the RF heating method, 250 Kg samples of Utah tar sands have been heated to 150°C. At 100° to 150°C, the viscosity of the bitumen is reduced to 100 cp, depending on the specific deposit. This viscosity permits production by various means, using the tubular electrodes as recovery paths.

One production method is by fluid replacement. Small laboratory experiments using 1 wt. percent sodium orthosilicate solution gave recoveries of 80 to 85 percent. Based on computer simulation, a gravity-drive method also appears promising. A high recovery rate is possible due to the relatively close spacing of the tubular conductors.

Electrodes may be emplaced in boreholes drilled from the surface, but preferably for the Utah deposits from pre-mined drifts. Mining and drilling costs are estimated to be $1 per barrel of recovered bitumen, and total costs in the order of $6 per barrel of bitumen.

INTRODUCTION

The IITRI RF Process is being developed to economically recover bitumen from Utah sands by strip-mining and above-ground processing. Proposed in situ processing, based on conventional heating methods, would have economic advantages and avoid severe environmental problems. However, the fundamental problem with previous in situ techniques is the difficulty in transferring heat by conventional methods, since the deposits are poor thermal conductors and are nearly impermeable to fluids.

IIT Research Institute (IITRI) has overcome the heat transfer problem by the invention of an efficient radio frequency power deposition technology suitable for heating very large in situ volumes of tar sands. This technology permits the simultaneous heating of the tar sand without thermal conduction or convection. The technology involves inserting special patterns of tubular conductors in boreholes and applying RF energy to the conductors at a frequency which is tailored to the electrical characteristics of the resource to be heated. The choice of the proper conductor pattern and operating frequency insures that virtually all of the applied RF power is contained and does not leak out to cause interference problems. Further, the selected operating frequency allows 100 m or greater penetrations of the RF energy into the resource so that $10^3$-$10^5$ m$^3$ blocks of tar sand can be simultaneously heated, thus minimizing electrode emplacement costs. Unlike previous applications of electrical energy to tar sand processing, the IITRI technology does not require any ambient moisture content in the resource to deposit energy, since RF heating can take place via the excitation of displacement currents. Further, the IITRI process is designed to maximize energy efficiency by strictly bounding the electromagnetic excitation volume, and by limiting non-uniformities of the pattern of energy deposition.

The IITRI RF heating process offers the potential for rapidly recovering low viscosity oils (after heating) from the deposits. The large number of electrodes which are employed can also serve as closely-spaced producer wells. The close spacing greatly hastens recovery, and leads to higher overall recoveries. Other potential advantages include high net energy ratios because of the efficient utilization of electrical energy; high overall resource utilization because the heating patterns are precisely defined; minimal environmental problem because of the in situ nature of the process; and attrac-
tive economics because of the process efficiencies, rapid production rates, and moderate capital equipment requirements. Presently, IITRI is under contract with the U.S. Department of Energy to explore on a laboratory basis the technical feasibility and economic potential of the IITRI RF process as applied to the Utah tar sand deposits. This paper presents the research progress to date.

THE UTAH TAR SAND RESOURCE

The Utah tar sand deposits are estimated to contain over 26 billion barrels of oil in-place (Campbell 1975; Ritzma 1973). These appear in some six deposits of economic significance (Oblad 1977) as summarized in Table 44-1.

A partial review of existing literature (Holmes 1948; Ritzma 1973; Byrd 1970; Wood 1972 and Peterson 1974), and contact with tract owners (Madsen 1979; Wall 1979) established the presence of thick (> 10 m) and relatively rich (> 7%) layers. These deposits have low moisture content (<1%), exhibit some saturated or in-place permeability (> 100 mD), contain no gas, and generally exhibit some dip (~ 20°). Environmental and overburden considerations favor a mining method of electrode emplacement which minimizes surface disturbances.

THE RF HEATING CONCEPT

The RF recovery concept as applied to the tar sand deposits is essentially a two-step process. First, the deposit is heated almost uniformly by means of RF energy to reduce the viscosity of the bitumen. Following this heating, some form of petroleum extraction process can be employed. An alternate to this process might be heating of the deposit to a point where the bitumen cracks in place to form a light oil and a carbon residue. This option may be advantageous in spite of the higher heating costs because the upgrading costs can be avoided.

Past Attempts

In the past there has been considerable interest in applying electrical energy in some way to recover useful fuels from in-place hydrocarbon deposits. These approaches seem to have failed because they did not uniformly heat the involved resource or depended upon ambient water to provide electrical conductivity.

The simplest approach has been the embedding of some simple electrical heating elements into the deposits (Ljungstrom 1951; Solomonson 1953). While this approach is technically feasible, it results in non-uniform conduction heating around the boreholes. This makes inefficient use of the applied energy.

60 Hz ohmic heating methods have been proposed in which electrical currents are passed through the tar sand deposit. Typically (Flock 1975), a simple pair of electrodes is placed within the deposit and a 60 Hz voltage is applied. However, this method encounters a number of difficulties. First, ac current flows between the electrodes largely because the presence of water in the deposit allows mobile ions to lower the observed electrical resistance. However, as heating continues, high current densities near the electrodes evaporate the local moisture, terminating the heating process. Attempts to mitigate this effect have included the injection of saline water from the electrodes and pressurizing the deposit to suppress vaporization. Even if these techniques are successful, the current-density is high near the electrodes, which causes inefficient deposition of electrical energy and consequent unfavorable economics. Many of the Utah tar sand deposits appear to be poor candidates for this approach because of their low moisture, and because the thin overburden makes pressurization difficult.

Other approaches involve the use of very high-frequency or microwave dielectric heating (Albernathy 1974). Such methods envision dropping antennas into boreholes. While this results in a volumetric heating method, it results in overheating near the antenna and underheating at a distance.

Deposition Efficiency

Because of the high cost of electrical energy, over- and underheating leads to significant waste of energy and to high costs. In Figure 44-1, it is assumed that the electric field intensity or electric current density falls off at r⁻¹, where r is the radial distance from the electrode. This is a reasonable assumption in the vicinity of electrodes, since near-cylindrical symmetry can be assumed. The tar sand heating rate is proportional to E²(r), and this is plotted as a function of the radial distance r as shown in Figure 44-1B.

Ideally, a uniform rate E₀² is desired over a precisely-controlled penetration length, L. However, the curves in Figure 44-1, due to typical antennas, electrodes, or other types of applicators, have peaks which cause excess heating above E₀² and tails which cause underheating beyond the limits of L. Thus, the area of the curve exceeding E₀² represents excess heating and the area beyond L represents wasted heat, since this tar is underheated and produces little or no product.

Table 44-1. Extent of Utah Tar Sand Deposits

<table>
<thead>
<tr>
<th>Deposit</th>
<th>In-place Bitumen billion bbl</th>
<th>Approximate Wt. % Bitumen in Tar Sand ¹</th>
<th>Overburden, ft, ²Walters (1974)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tar Sand Triangle (S.E. Utah)</td>
<td>12.5-16.0</td>
<td>5¹</td>
<td>0-2000</td>
</tr>
<tr>
<td>P.R. Spring (N.E. Utah)</td>
<td>4.0-4.5</td>
<td>6²</td>
<td>Shallow</td>
</tr>
<tr>
<td>Sunnyside (N.E. Utah)</td>
<td>3.5-4.0</td>
<td>9³</td>
<td>0-150</td>
</tr>
<tr>
<td>Circle Cliffs (S.E. Utah)</td>
<td>1.31</td>
<td>5¹</td>
<td>0-1800</td>
</tr>
<tr>
<td>Hill Creek (N.E. Utah)</td>
<td>1.16</td>
<td>8⁴</td>
<td>—</td>
</tr>
<tr>
<td>Asphalt Ridge (N.E. Utah)</td>
<td>1.048</td>
<td>8²</td>
<td>0-500</td>
</tr>
</tbody>
</table>

¹ Seeps and pools are discounted as not being representative of the deposit. Superscripts refer to the following references:
1. Wood and Ritzma (1972)
2. Campbell (1975)
3. Holmes, Page, and Averitt (1948)
The application efficiency of electromagnetic energy is the area of the crosshatched rectangle, $E_0^2 (L-R)$, divided by the area under the curve, $E^2 (r)$. It can be shown analytically that the maximum application efficiency will quadruple electrical power requirements and related investment. For a viable process, in situ electromagnetic field applicators must be designed to contain and excite a nearly uniform electric field over a large volume to achieve an application efficiency approaching 100 percent.

The RF Heating Step of the IITRI Process

To overcome these limitations it is necessary to create a uniform electric field or uniform current density within the deposit over a precisely defined volume. This ideally would be possible by burying within the earth two parallel plates which have large areal dimensions compared to the plate separation. If a voltage were applied to these plates, a substantially uniform electric field between the plates could be realized. However, the exposed edges of the parallel plates would also induce currents in the adjacent formation, leading possibly to environmental problems and to radiation at the higher radio frequencies. These would represent an inefficient use of electrical energy.

Leakage fields or radiation can be completely avoided by the use of a tri-plate line configuration. Here, three parallel plates are buried in the deposit, and the inner plate is excited with respect to the two outer plates. The outer plates are also connected at the sides to totally enclose the electric field in a "shielded box". Such an arrangement is shown in Figure 44-2A. A tri-plate configuration can be practically realized using conventional drilling techniques by the cylindrical conductor array shown in Figure 44-2C, consisting of rows of buried tubular conductors. It can be shown that the desired energy confinement and uniform properties of the flat plate configuration are retained by this array, if certain design practices are followed.

Such an array of tubular conductors can be emplaced either from the surface (in the case of very shallow deposits where surface disturbances are permissible), or from mine drifts or cross-cuts. In the case of the Utah tar sand deposits, surface emplacement does not appear practical because of rugged local terrain and environmental disturbance. Further, more rapid recovery is possible via mined cross-cuts below the deposit. Hence, mining methods for electrode emplacement are considered likely.

A conceptual embodiment of such an electrode emplacement for the Sunnyside deposit is indicated in Figure 44-3. The Sunnyside deposit outcrops on a mountain side, and access is made via mined adits. Several rich layers are available 20 m or more thick, which permit separation of the adits by approximately 10 m. Horizontal emplacements of electrodes are made via boreholes drilled from the adits. After emplacement, the RF energy is applied to the inner row with respect to the outer rows. This creates a nearly uniform electric field which heats the deposit uniformly until the viscosity has been adequately reduced.

After heating, the deposit may be produced by gravity flow into the lowest row of electrodes, which are installed.

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![Figure 44.1 Application Efficiency Considerations](image)

- **A** Long cylindrical electrode in borehole
- **B** Heating rate, $E^2 (r)$, as a function of radial distance, $r$, in the immediate vicinity of the electrode and the cylinder radius $R$. 

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to collect the liquid. Other types of production methods can also be considered; these are considered in the Production Step described in Section 4.

**RF Properties of Utah Tar Sands**

The term RF or radio frequency generally refers to those frequencies which are employed in wireless communication. These frequencies can be as low as 45 Hz (as employed in a prototype submarine communication system), or extend well above 10 GHz (as employed for satellite communications systems). However, the frequencies which are of principal interest to heat Utah tar sand deposits are in the range of 0.01 MHz to 10 MHz. These frequencies permit electromagnetic wave penetration of 100 m into typical deposits while at the same time generating absorbed power densities of about 0.1 watt per kilogram for conservative values of electric field intensity. Higher frequencies, such as in the microwave band, have much reduced penetration and cannot be easily employed to heat in situ the large volumes that are required for an economic implementation of the process. Lower frequencies have much reduced absorbed power densities and cannot be easily employed to heat in situ at a rate high enough for good process economics, unless excessive electric fields are used (with the possible consequence of catastrophic spark-over of the formation). The precise frequency of operation would ideally be determined by the constitutive electrical parameters of the formation of interest, since these parameters determine conversion of RF energy into heat and the maximum conservative applied electric field.

The electrical characteristics of earth media are considered in terms of the behavior of lossy dielectrics (Von Hippel 1954). In particular, the behavior of tar sands, even when extremely conductive on a bulk basis, is considered that of a heterogeneous dielectric (Pierce 1973). Such a material is defined as a low-loss dielectric matrix or particle pack impregnated with a partially-conducting aqueous solution. This is the case for the Asphalt Ridge deposit, which exhibits very lossy characteristics when moist (about 7 percent water), but upon evaporation of the water becomes a low-loss dielectric. The Sunnyside deposit is dry prior to testing; and, therefore, behaves only as a low-loss dielectric.

For the general case of electromagnetic heating of earth media it is appropriate to consider relationships in terms of the complex dielectric constituents. The heating, $P^\parallel$, per unit volume in a lossy medium exposed to an electric field of amplitude, $E$, oscillating at the angular frequency, $\omega$ ($\omega = 2\pi f$; where $f$ is in Hertz), is

$$P^\parallel = \frac{1}{2} \varepsilon_0 \varepsilon_r \omega |E|^2 \text{ watts/m}^3$$

where

$$\varepsilon_0 = 8.85 \times 10^{-12} \text{ F/m},$$

and $\varepsilon_r$ is the property of the lossy medium defined by the permittivity relationship

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r''.$$  

Here $\varepsilon_r'$ is the more familiar relative dielectric constant, and the loss tangent, $\tan \delta$ is defined as

$$\tan \delta = \frac{\varepsilon_r''}{\varepsilon_r'}.$$

Typical data for a dry tar sand deposit are shown in Figures 44-4 and 44-5 which present, respectively, the rela-

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**Figure 44.2** Uniform Heating Electrode Array Evolution  
(A) Fully-shielded tri-plate;  
(B) Tri-plate line open-side equivalent; and  
(C) Cylindrical conductor array equivalent

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Figure 44.3 Conceptual design of RF process for Sunnyside deposit
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tive permittivity and loss tangent. The actual values pose no basic limitation in the case of the tri-plate line in situ excitor, since this structure can propagate any frequency; and, therefore, any frequency can be used which is optimum for the deposit. As a consequence, it is possible to employ a frequency where the heating and penetration characteristics are optimized. This is not feasible with other types of possible excitors, such as antennas which require the antenna size to be comparable to a wavelength. Since very long wavelengths may be needed for moist deposits, the antenna approach becomes impractical.

The dielectric breakdown characteristics of the Utah tar sands provide an upper bound on the maximum heating rate which is allowable near the electrode or for the deposit as a whole. In attempts to break down samples of the Utah tar sand deposits for various moisture conditions and temperatures, it was not possible to induce breakdown with IITRT's present equipment, which produces maximum field intensities in the order of $10^8$ V/m.

Large Sample RF Heating Studies

The RF heating of large tar sand samples by a tri-plate

![Figure 44.4 Relative permeability of Sunnyside deposit sample](image-url)
line was studied both analytically and experimentally. An example of the analytical studies is shown in Figure 44-6, which depicts the computed heating within a 24-foot thick tri-plate line. (This size line would be appropriate for pilot-scale field experiments.) Here, a finite-difference computer code was used which takes into account the exact spatial distribution of RF power absorption, as well as the thermal characteristics of the resource. In this Figure, Cut 2 graphs the temperature variation on a line perpendicular to the rows of the tri-plate, but midway between electrodes. Cut 1 graphs the temperatures on a similar line but which intersects the electrodes. The zero position represents the center electrode, and positions 0.5 and -0.5 represent the outer or guard planes. Note that the peaking effects near the electrodes are minimized by utilizing a fairly low absorbed RF power density and allowing thermal diffusion effects to further promote heating uniformly. These and other similar results demonstrate that nearly uniform RF heating is possible for large in situ volumes.

![Figure 44.5](image-url)

*Figure 44.5*  Loss tangent-Sunnyside deposit sample
Several large samples of the Utah tar sand deposits were RF heated in the laboratory. A 70 Kg sample was heated to 250°C and two 250 Kg samples were heated to 150°C. The samples employed for these tests contained 6 to 7 percent water. Measurements of the electrical input impedance to the tri-plate line indicate that the moisture of each sample initially evaporated near the electrodes to form a dry, non-conducting dielectric sheath surrounding the electrodes. The RP heating process, however, could be continued without interruption.

RF leakage measurements were also conducted on a scale model of the tri-plate line. These measurements

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Cut 1</th>
<th>Cut 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>350°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>250°C</td>
<td>\</td>
<td>-</td>
</tr>
<tr>
<td>150°C</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>100°C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Both curves. After 304 hours at an average RF power density of 0.28 W/kg.

\[ D = 24' \]

Normalized position, \( x/D \)

Figure 44.6 Temperature rise within a 24-foot thick tri-plate line with 6-inch diameter electrodes located at 3-foot intervals in the excitor and shield planes (304 hours to 200°C).
demonstrate that both the nearby and distant leakage is quite small, such that the heating rate just outside the conductor array is only $10^5$ times that within the array. This permits normal activity for work or radio reception at the site.

It should be mentioned that some deposits will have layers which have different constitutive electrical properties. Some tailoring of the heating rates within the different layers is also possible with the RF process to enhance certain recovery processes, such as fluid replacement. This can be done by proper electrode positioning and frequency selection.

THE RECOVERY STEP OF THE IITRI PROCESS

To achieve reasonable rates of product recovery by in situ tar sand processes, it is necessary to lower the viscosity of the bitumen, since the rate of flow of bitumen within the deposit is inversely proportional to the viscosity. The viscosity of bitumen from Utah tar sand deposits is in excess of 10^5 cp under reservoir conditions and can be reduced to about 100 cp by heating the deposits to about 125° to 150° C (Dorrence 1978). Under such conditions, the bitumen can be recovered either by gravity-drive or by replacement with a suitable surfactant solution. The bitumen can also be pyrolyzed in-place and the product oil can be recovered by gravity-drive. IITRI's preliminary findings on the applicability of the gravity-drive and fluid replacement recovery techniques to Utah tar sand deposits will be discussed in this section.

Fluid Replacement

The replacement of hot bitumen from the surface of sand grains by a surfactant solution is similar to tertiary oil recovery using surfactant or micellar flooding techniques. Several mechanisms have been proposed to explain the replacement phenomenon, but the chemistry of replacement is still not well understood due to a lack of theoretical information.

<table>
<thead>
<tr>
<th>Property</th>
<th>C-1</th>
<th>C-2</th>
<th>C-4</th>
<th>Run no:</th>
<th>C-6</th>
<th>RF-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of charge to reactor, g</td>
<td>2533</td>
<td>1945</td>
<td>1975</td>
<td>2671</td>
<td>1780</td>
<td></td>
</tr>
<tr>
<td>Bitumen content, wt. % before replacement</td>
<td>12.70</td>
<td>12.70</td>
<td>10.06</td>
<td>9.46</td>
<td>12.70</td>
<td></td>
</tr>
<tr>
<td>Bitumen extraction during fluid replacement, %</td>
<td>83.0</td>
<td>83.5</td>
<td>80.0</td>
<td>62.3</td>
<td>76.0</td>
<td></td>
</tr>
<tr>
<td>Volume of sodium silicate solution used, liters</td>
<td>13.5</td>
<td>22.3</td>
<td>8.82</td>
<td>0.99</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td>Bulk density of tar sand core, g/cc</td>
<td>1.76</td>
<td>1.37</td>
<td>1.37</td>
<td>1.85</td>
<td>1.73</td>
<td></td>
</tr>
<tr>
<td>Core temperature during fluid replacement, °C</td>
<td>150</td>
<td>150</td>
<td>100</td>
<td>150</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Method of heating *</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>RF</td>
</tr>
</tbody>
</table>

* C = Core was heated by electrical heaters from outside of reactor. RF * Core was heated by RF energy.

Bench-scale experiments were conducted to investigate recovery of bitumen by a fluid replacement technique after uniform heating of the deposit to the required temperature. Samples of unconsolidated tar sand from Asphalt Ridge were used in this study. A 1 wt. percent sodium orthosilicate solution was used for flushing. The apparatus is shown in Figure 44-7. A well-packed sample of tar sand was heated to the desired temperature using either volumetric RF heating or conventional external heating elements, and a silicate solution preheated to the same temperature as that of tar sand core was pumped to replace the bitumen. The properties of the tar sand used in these experiments, the operating conditions, and the recovery of bitumen are shown in Table 44-2.

The solution was pumped into the reactor under pressure, allowed to soak for 30 minutes, and was then collected by slowly replacing it with fresh solution. The procedure was repeated until no bitumen was observed in the products. However, in experiment C-6, the solution was allowed to soak in the reactor overnight and the flooding procedure was repeated only twice.

The results from the laboratory tests indicate that up to 80 percent of the total bitumen can be recovered by replacement with sodium silicate solutions after uniform heating of the tar sand samples. In the field, it is planned to introduce the flushing solution from the bottom row of electrodes and to collect the replacement products from the top row for one conceptual design as illustrated in Figure 44-2. Under this approach, the fluid travels in the vertical direction perpendicular to the bedding planes. This procedure should minimize the break-through problems attendant a horizontal sweep where only the more permeable layers are effectively swept.

The total volume of solution consumed in each test and the packing density of the sand indicates that loosely packed sand requires a larger amount of solution. Due to the nature of the unconsolidated tar sand, it was not possible to achieve sand densities greater than 1.85 g/cc in the laboratory. It is believed that solution consumption will be

Table 44-3. Assumed Relative Permeability of Utah Tar Sand Core to Bitumen and Gas

<table>
<thead>
<tr>
<th>Bitumen Saturation</th>
<th>FRACTIONAL PERMEABILITIES</th>
<th>Core to Bitumen and Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of Pore Space</td>
<td>^Bitumen</td>
<td>^Gas</td>
</tr>
<tr>
<td>1.00</td>
<td>0.95</td>
<td>0.00</td>
</tr>
<tr>
<td>0.90</td>
<td>0.95</td>
<td>0.00001</td>
</tr>
<tr>
<td>0.80</td>
<td>0.75</td>
<td>0.004</td>
</tr>
<tr>
<td>0.70</td>
<td>0.45</td>
<td>0.016</td>
</tr>
<tr>
<td>0.60</td>
<td>0.25</td>
<td>0.03</td>
</tr>
<tr>
<td>0.50</td>
<td>0.20</td>
<td>0.05</td>
</tr>
<tr>
<td>0.40</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>0.30</td>
<td>0.0002</td>
<td>0.12</td>
</tr>
<tr>
<td>0.20</td>
<td>0.00001</td>
<td>0.29</td>
</tr>
<tr>
<td>0.10</td>
<td>0.00</td>
<td>0.60</td>
</tr>
<tr>
<td>0.00</td>
<td>0.00</td>
<td>0.99</td>
</tr>
</tbody>
</table>
RADIO-FREQUENCY HEATING TO RECOVER OIL FROM UTAH TAR SANDS

Figure 44.7 Fluid replacement apparatus

significantly lower under field conditions because the densely-packed deposit in the natural state has less void volume. It is also believed that longer soaking times and flushing from the bottom up will minimize the solution requirement. Other tertiary recovery techniques, such as the use of a high-viscosity polymer “slug” should further reduce fluid consumption.

Gravity-Drive

Production of the heated bitumen by gravity-drive, possibly assisted by autogenously developed gas drive or by gas injection, may be preferred to replacement by a surfactant solution. This is because gravity drive avoids the usage and cost of surfactant solutions and the environmental concerns for their disposal. In addition, by proper placement of the producing electrode boreholes, it should be possible to minimize the effect of permeability discontinuities in the deposit.

It is not possible to experimentally investigate gravity-drive on a small scale in the laboratory, but it is possible to theoretically predict the rate of gravity-drive production with the help of commercially available reservoir simulation models and core data from the selected deposit. The ALPH78 simulation model available at Texas A&M University (Morse 1978) has been used in this study in order to simulate a 50-ft. thick seam of Utah tar sand.

A porosity of 30 percent by volume and 60 percent pore space saturation with bitumen were used in this calculation. Very limited information is available on the distribution of impermeable layers and relative permeability of the deposit to the wetting (oil) and nonwetting (gas) phases as a function of bitumen saturation. The assumed unsaturated and relative permeability values are shown in Tables 44-3 and 44-4. However, the unsaturated permeability values used in the 5 layers represent the typical distribution of permeability in Utah tar sand deposits (Rail and Tailiaferro 1949; Gwynn 1971).

The rate of production of bitumen was calculated under similar conditions using four different production well designs, summarized in Table 44-5. The calculated results are given in Figure 44-8, where the cumulative production of bitumen expressed as percentage of the total in-place is shown as a function of time of production. The results shown in this figure cannot be considered to be quanti-
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tative until precise chemical and physical characterization of the selected deposit is done. However, it is valid to compare the rate of production predicted for the underground electrode assembly to that predicted for conventional production methods.

Table 44-4. Assumed Distribution of Unsaturated Permeabilities in Utah Tar Sand Deposit

<table>
<thead>
<tr>
<th>Layer Thickness</th>
<th>Unsaturated Permeability, mD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7 m (9.0 ft)</td>
<td>2000</td>
</tr>
<tr>
<td>2.7 m (9.0 ft)</td>
<td>1000</td>
</tr>
<tr>
<td>2.7 m (9.0 ft)</td>
<td>2000</td>
</tr>
<tr>
<td>2.7 m (9.0 ft)</td>
<td>350</td>
</tr>
<tr>
<td>4.2 m (14.0 ft)</td>
<td>2000</td>
</tr>
<tr>
<td>15m (50 ft) TOTAL</td>
<td>1700 Weighted Average</td>
</tr>
</tbody>
</table>

Table 44-5. Summary of Conditions for Figure 44-8 for Gravity-Drive Using Air Replacement at Several Atmospheres

<table>
<thead>
<tr>
<th>Case</th>
<th>Method of Emplacement of Producing Wells</th>
<th>Spacing of Producing Wells</th>
<th>Description of Producing Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Vertically downward from surface</td>
<td>on 40m centers</td>
<td>0.15 m dia. pipe perforated over 3 m from bottom</td>
</tr>
<tr>
<td>II</td>
<td>Vertically upward from panel drift</td>
<td>in 20m rows spaced every 10m within row</td>
<td>0.15 m dia. pipe perforated over 3 m from bottom</td>
</tr>
<tr>
<td>III</td>
<td>Upward at varying angles from panel drift</td>
<td>on 3 m centers</td>
<td>0.07 dia. holes drilled just into base of deposit</td>
</tr>
<tr>
<td>IV</td>
<td>Horizontally from panel drifts</td>
<td>every 3 m in a horizontal row at deposit base</td>
<td>0.15 dia. horizontal pipe perforated over entire length at base of deposit</td>
</tr>
</tbody>
</table>

Figure 44.8 Cumulative production for various electrode arrangements
The rate of production of bitumen predicted by use of conventional production wells spaced every 40 m and drilled from the surface is shown as case I in Figure 44-8. In the RF heating process, the electrodes will be drilled into an unconsolidated deposit from an underlying bed of limestone. For this purpose, 2.5 m by 4 m panel drifts are formed from a master drift, and then electrodes are drilled into the overlying resource from these panel drifts. The hot bitumen will be allowed to flow into these panel drifts under gravity and will subsequently be pumped up from a central location in the master drift. The predicted rate of production of bitumen using a separation of 20 m between adjacent rows of electrodes for a production hole separation of 10 m is shown as case II. The production rate, under such circumstances, can be increased by perforating the low-permeability limestone or siltstone layer underneath the unconsolidated tar sand deposits. The rate of production calculated with holes drilled radially from the panel drift into the bottom of the deposit at regular intervals of 3 m is shown as case III in the same Figure.

In the case of consolidated deposits, the compressive strength of the bitumen saturated sandstone layers is of the order of 3000 psi (Johnson, et. al, 1975) and it is possible to drill electrodes horizontally from the adits into the deposit. The strength of these sandstone layers permits conventional mining methods for electrode emplacement. Conceptual design of such an electrode arrangement is shown in Figure 44-3. The hot bitumen can be recovered from the perforated bottom row of electrodes that penetrate the entire length of the deposit. Measured electrical parameters of consolidated tar sand samples from the Sunnyside location suggest a spacing of 3 m between two electrodes in the same row. The rate of production of bitumen from such an electrode arrangement is shown as case IV in Figure 44-8.

The predicted production of bitumen in 1000 days is about 30 percent of the total bitumen in-place in case I, 55 percent in case II, 70 percent in case III, and 80 percent in case IV. Although these results are qualitative in nature, they clearly suggest that significantly higher production rates can be achieved by use of closely spaced producer wells. The rate of production with the IITRI underground electrode emplacement techniques appears to be 3 to 5 times higher than the more conventional petroleum well spacing embodied in Case I. This is a significant advantage, especially when the economics of cash-flow analyses are applied.

**NET ENERGY RATIO ANALYSIS**

Under the IITRI process, the Utah tar sand deposits would be heated in situ by RF energy to either 100° C or 150° C to allow recovery of the bitumen by either replacement with surfactant solution or by gravity-drive. Net energy ratio calculations for gravity-drive were done to evaluate the energy efficiency of this process for tar sand with 9 wt. percent bitumen and 1 wt. percent water, assuming the above two process temperatures. The average specific heat of the deposit was estimated at 0.23 Btu/lb.-° F using the triangle correlations from the Cameron Engineers Handbook (Hendrickson 1975). The net energy ratio values were computed by dividing the energy content of the extracted bitumen by the energy consumed in the ac power plant.

The computed net energy ratios are shown in Figure 44-9 as a function of the percentage of the total bitumen extracted. The input energy to the process was calculated assuming either a 33 percent ac power generation efficiency, for a combined-cycle plant (Guy and Woodward 1972; Commonwealth 1979). An efficiency of 90 percent was chosen for the generation of RF energy from ac, based on manufacturers' estimates (Bullock 1976a). Finally, an efficiency of 95 percent was taken as the degree of effective deposition or application of the generated RF energy as useful heat energy within the deposit, based on energy deposition studies discussed in Section 3.

A favorable net energy ratio of 5 to 12 appear to be likely with the RF dielectric heating process depending on the grade of the deposit and the process conditions used in the calculations.

**ECONOMIC CONSIDERATIONS**

The major operating costs are for electrical power and for mining and drilling. Preliminary results of studies currently being conducted by Commonwealth Associates suggest (Commonwealth 1979) an approximate cost of 2\(^2\)/kwhr for power which is also instantly interruptible and consumed in off-peak periods. Sufficient off-peak generation capacity exists in Utah-Colorado to supply energy requirements for a fairly sizable group at RF recovery plants. Based on 2\(^2\)/kwhr, a specific heat of 0.23 Btu/lb.-° F, an application
AC power costs per barrel for RF heating of Utah Tar Sand

Figure 44.10

Other operational costs for the expendable electrodes, pumping of bitumen, and RF generator maintenance are in the order of $1/bbl for the 70 percent recovery of the 9.4 percent by weight deposit. In the case of production of bitumen by replacement with surfactant solution, the estimated cost of surfactant loss, heating of the replacement fluid, recirculation water treatment, and bitumen separation from flushing solution are expected to increase the cost of production by $0.80 to $1.25 per barrel of bitumen. The increase in cost due to replacement of bitumen by surfactant solution will be partially offset by lower heating costs as the temperature required in this case is believed to be lower than the temperature required for production by gravity drive.

The major capital equipment is the RF generator which, for the 10,000 bbl/d Sunnyside example, would cost about $8 million (Bullock 1976b). Other capital equipment costs includes $7 million for mining equipment (Cleveland 1979).

The bitumen produced by the gravity-drive and fluid replacement methods will have to be upgraded into syncrude at a cost in the order of $5/bbl. IITRI has not yet examined the trade-offs between added power costs and upgrading cost reduction for the case when the bitumen is pyrolyzed in situ to produce a liquid product which requires little or no upgrading.

CONCLUSIONS

Based on laboratory and analytical work to date, it appears that the IITRI RF recovery process, as applied to the Utah tar sand deposits, is technically feasible and economically attractive. IITRI has demonstrated that large blocks of the Utah deposits can be uniformly heated without catastrophic electrical breakdown. The large number of electrodes used can greatly enhance the rate of recovery. This implies the total recovery will be similarly increased within an economically meaningful time period. The preliminary economic assessment suggests that the process, including provisions for upgrading and recoveries less than used in the examples, should produce a syncrude which is quite competitive with current world oil prices.

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