Field Experiment of In-Situ Oil Recovery from a Utah Tar Sand by Reverse Combustion

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Tar-sand-oil-recovery research at the Laramie Energy Research Center, ERDA, is reviewed. The status and current results of an associated field experiment scheduled to start in 1975 in the Northwest Asphalt Ridge deposit near Vernal, Utah, to test in-situ oil recovery by reverse combustion.

INTRODUCTION

Part of the mission of the Energy Research and Development Administration (ERDA) is to develop all energy sources to meet the needs of present and future generations. Toward that mission the Laramie Energy Research Center (LERC) is conducting research and field experiments for the development of recovery methods applicable to important supplemental sources of oil and gas. These experiments involve: (1) in situ oil recovery from oil shale, (2) underground gasification of coal, and (3) in situ oil recovery from tar sands. This report is concerned with the latter on which research was begun about 6 years ago. The objectives of this research are twofold: To determine the physical characteristics of known tar sand deposits and their probable effect on oil recovery, and to develop and field test in situ methods applicable to the recovery of oil from tar sands.

In 1971, a laboratory was established at LERC for analysis of tar sand samples. Since then, over 3,000 samples, mostly from coring in 12 Utah deposits and a New Mexico deposit, have been analyzed. Three reports have been published (6,3., ,y giving results of analysis of cores that were taken from 12 wells in the P. R. Spring deposit by the Utah Geological and Mineral Survey. Average characteristics for several of the largest Utah deposits are summarized in this report.

In 1973, a study was made of in situ oil recovery methods that have potential for recovering oil from tar sands. All of the methods considered involve means for reducing viscosity as well as supplying energy for displacement of the bitumen. Reed, Reed, and Tracht (7) in 1959 reported results of experimental investigation of reverse combustion in tar sands. It was shown that the process has particular advantages for tar sand bitumen which is relatively immobile. They concluded that field application would depend on the existence of adequate air permeability to permit the required relatively high air flux to be injected. Trantham and Marx (3) reported results of reverse combustion oil recovery experiments made by Phillips Petroleum Company in 1955 to 1958 in a 60-ft. deep and 6 to 12-ft. thick tar sand near Bellamy, Missouri. In some of the tests, sustained reverse combustion was achieved in the tar sand which had average effective air permeability with bitumen and water in place of 250 md. at the time of ignition.
Although there are some serious disadvantages with reverse combustion, it appeared that reverse combustion offered the best potential of known methods for in situ oil recovery from tar sands. As a result, laboratory combustion tube experiments were conducted in 1979 using tar sand from the P. R. Spring and Asphalt Ridge deposits in northeastern Utah. The purposes of these experiments was to extend this earlier work and to further evaluate the potential of the process for application to the two areas being considered for field experimental sites. Reported results of these combustion tube experiments have led to the design of a field experiment. The selection and development of the field experiment site and the initiation of the first of several planned field experiments are the principal concerns of this report.

U. S. TAR SAND RESOURCE

Tar sand is a term applied to a variety of rock types that contain some form of bituminous material (I). The term is quite descriptive of certain types of rocks and their associated viscous hydrocarbons, but it is a misnomer. Tar is defined as a refined product and sand properly describes unconsolidated particulate mineral matter. As used, tar sand refers to consolidated or unconsolidated rocks with interstices that contain very viscous to solid bitumen which, in its natural state, cannot be recovered by primary petroleum production methods. Other terms applied to this material have included: Bituminous sandstone, oil-impregnated rock, oil sand, and rock asphalt. Any distinction that can be made between tar sands and so-called "heavy oil" deposits would relate to differences in viscosity of the contained bitumen or oil. In the case of tar sand the bitumen is so viscous or immobile as to prevent displacement and production by primary petroleum production methods; whereas the "heavy oils" can be produced by primary methods, but not at economic rates. In this report, the hydrocarbon found in tar sands is referred to as "oil" or "bitumen" interchangeably.

About 56 tar sand occurrences have been reported in 22 states (2). Partial resource estimates have been made in seven states. The resource in known deposits in five of the states (California, Kentucky, New Mexico, Texas and Utah) is estimated at up to 29 billion barrels of oil. Most of this estimated resource is in Utah where 2k deposits contain an estimated 28 billion barrels of oil (8). Six of these deposits which are shown in Figure 1, are classed as giant deposits containing from about 1 billion to as much as 16 billion barrels of oil each. Four of these deposits, Asphalt Ridge, Hill Creek, P. R. Spring, and Sunnyside, are in the Uinta Basin; they contain over 10 billion barrels of low sulfur (less than 0.5 wt. %) oil which is a prime target for current interest in developing production from tar sands.

TAR SAND CHARACTERISTICS

Of the more than 3,000 Utah tar sand samples that have been analyzed at LERC, most have come from the six largest deposits in the state. Some average properties for these deposits are shown in Table 1. The number of samples analyzed is too small for these data to be considered representative of such vast deposits. However, they show that generally the deposits have good porosity and permeability, are less than 50% saturated with bitumen, and have compressive strength indicative of consolidated rocks. Even Asphalt Ridge, which is generally thought of as a relatively unconsolidated tar sand similar to the Athabasca deposit in Canada, shows a fairly high average compressive strength of 1,632 lb./sq. in. after bitumen extraction, compared to 2,91 lb./sq. in. before bitumen extraction as shown in the Table. Average permeability determined before bitumen extraction ranges from less than 25 md. for the Tar Sand Triangle to over 500 md. at P. R. Spring, and indicates that in many of the deposits there is adequate permeability for fluid injection. Average water saturation at P. R. Spring and Asphalt Ridge is less than 8%. These deposits are above ground water level and fluid containment would probably be a problem with fluid injection for oil recovery purposes.

COMPARISON OF REVERSE AND FORWARD COMBUSTION

The two in situ combustion processes, forward and reverse, are shown in Figure 2. In forward combustion, ignition occurs at the air injection well and a combustion front moves through the formation in the direction of air flow toward the production well. In this process, coke deposited from that part of the oil that is thermally cracked provides fuel for the combustion.
TABLE 1. AVERAGE PROPERTIES OF GIANT TAR SAND DEPOSITS IN UTAH

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Samples No.</th>
<th>Type</th>
<th>Porosity, %</th>
<th>Permeability, md</th>
<th>Bitumen Sat., %</th>
<th>Water Sat., %</th>
<th>Compressive Strength, Ib./sq. in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt Ridge</td>
<td>120</td>
<td>C</td>
<td>19-6</td>
<td>497</td>
<td>51</td>
<td>2.7</td>
<td>2,491</td>
</tr>
<tr>
<td>Circle Cliffs</td>
<td>6</td>
<td>C</td>
<td>12.3</td>
<td>228</td>
<td>17.7</td>
<td>-</td>
<td>6,555</td>
</tr>
<tr>
<td>Hill Creek</td>
<td>203</td>
<td>C</td>
<td>20.2</td>
<td>325</td>
<td>29.7</td>
<td>2.1</td>
<td>6,555</td>
</tr>
<tr>
<td>N.W. Asphalt Ridge</td>
<td>1,087</td>
<td>C</td>
<td>22.8</td>
<td>603</td>
<td>45-2</td>
<td>20.2</td>
<td>1,598</td>
</tr>
<tr>
<td>P.R. Spring</td>
<td>1,038</td>
<td>C</td>
<td>25-0</td>
<td>1,510</td>
<td>14.2</td>
<td>3.0</td>
<td>4,784</td>
</tr>
<tr>
<td>Sunnyside</td>
<td>129</td>
<td>C</td>
<td>21.3</td>
<td>729</td>
<td>44.8</td>
<td>-</td>
<td>7,805</td>
</tr>
<tr>
<td>Tar Sand Triangle</td>
<td>29</td>
<td>S</td>
<td>20.0</td>
<td>207</td>
<td>6.3</td>
<td>-</td>
<td>3,242</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>C</td>
<td>19-7</td>
<td>788</td>
<td>70.7</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

1/ S = Surface; C = Core
2/ Total liquid saturation, percent by weight
Forward combustion is more easily controlled and requires a lower air flux than the reverse process. However, oil and water vapors generated by the combustion front move forward into the unheated portion of the reservoir where they cool and condense. The bitumen will again become very viscous and tend to plug the pores in which it is deposited.

In reverse combustion, ignition is effected at the production well and the combustion front moves toward the air injection well in a direction counter to the direction of air flow. Movement of the burning front is a function of heat conduction ahead of the front. Some of the bitumen is burned and coke is left in the sand from thermal cracking of the bitumen. Reverse combustion has two main advantages over forward combustion for tar sands: (1) vaporized fluids move through the hot, burned-out part of the reservoir with no possibility of plugging, and (2) the oil produced is of higher quality than the original bitumen. However, the reverse combustion process is relatively more sensitive to air flux, which must be kept above a defined minimum or the process may turn around and burn in the forward direction. Also, spontaneous ignition might occur in the unburned portion of the reservoir as a result of low temperature oxidation if air injection is maintained for too long a period of time.

SOME RESULTS OF REVERSE COMBUSTION EXPERIMENTS

Laboratory investigation of the reverse combustion process was done at LERC to obtain basic information for the design of field experiments in Utah tar sands. The experiments were conducted under near adiabatic conditions in a 9-foot-long, 4-inch-diameter, thin-wall tube packed with crushed tar sand. A total of six combustion tests were made with tar sand from the P. R. Spring and Asphalt Ridge deposits. As obtained from these experiments (5), the increase of combustion temperature with increasing air flux is shown in Figure 3. Figure 4 shows that the combustion front velocity through the combustion tube is directly proportional to the air flux. The oil recovery obtained is also a function of the air flux as shown in Figure 5. The solid oil-recovery curves in Figure 5 are the published data of Reed, Reed, and Tracht (7) along which the data for Asphalt Ridge are superimposed.

Maximum recovery was obtained at an air flux of about 35 std. cu. ft./hr.-ft. As air flux decreases below 35 std. cu. ft./hr.-ft., recovery by reverse combustion decreases. However, the loss at the low air flux can largely be regained if reverse combustion is followed by forward combustion. This is reflected in the upper solid curve at air flux less than 35 std. cu. ft./hr.-ft. At higher air flux, there is a slight decrease in recovery as a result of increased burning of bitumen. The broken curves in Figure 5 show the oil recovery from the P. R. Spring experiments for which lower oil recovery is attributed to lower initial bitumen saturation than in the Asphalt Ridge samples.

These laboratory reverse combustion tests have shown that at the optimum air flux about 10% of the initial bitumen is burned, about 50% can be recovered, and the remainder, 40% is left deposited in the sand as coke. The recovered oil is a product of thermal cracking of the bitumen and has a gravity of about 23° API. This synthetic crude oil is of better quality than the original 10° API bitumen. Sulfur is reduced from 0.5% to 0.021, with about 95% of the sulfur left with the coke in the sand. Water, from vaporized interstitial water and water of combustion, approached one-half of the total produced liquids. Analysis of the produced gas shows that all of the oxygen in the injected air is consumed in the reverse combustion process. Small amounts of hydrogen, methane and ethane were detected in the gas from the higher temperature runs. DESIGN OF THE FIELD EXPERIMENT

Based upon results of the laboratory combustion tube experiments, plans were developed to test the reverse combustion process in a field experiment. A site in Northwest Asphalt Ridge deposit was selected because of its nearness to a community and because land was available for the experiment. The site is comprised of 10 acres of land owned by Sohio Petroleum Company and others, who made the land available through a cooperative agreement with LERC. Northwest Asphalt Ridge is situated off the northwest end of the prominent Asphalt Ridge from which it is separated by a fault. The site is only about 5 miles west of Vernal, Utah. Coring to evaluate the total tar sand section under
FIGURE 3: "EFFECT OF AIR FLUX ON PEAK TEMPERATURE.

FIGURE 4: "EFFECT OF AIR FLUX ON VELOCITY OF COMBUSTION FRONT.

FIGURE 5: "EFFECT OF AIR FLUX ON FRACTIONAL OIL RECOVERY.

FIGURE 6: STRATIGRAPHIC COLUMN AT EXPERIMENT SITE.
the site and to select a test zone was done late in 1974 and early 1975. Two coreholes were drilled: One near the northwest corner of the site and the other near the southwest corner. Figure 6 is a stratigraphic column showing depths and thicknesses of the rock formations under the experimental site. Surface elevation at the site is 5960 ft. above sea level. The top of the Rim Rock sandstone member of the Mesa Verde Formation occurs at depths of 200 to 300 ft.; dip of the Rim Rock is south-southwest at about 26°. The Rim Rock is about 100 ft. thick and contains several sections up to 37 ft. thick which are bitumen bearing and separated by shale or tight sandstone stringers. The Asphalt Ridge sand, beneath the Rim Rock, and the Duchesne River Formation above also contain bitumen.

An 11-ft.-thick tar sand section at 295 ft., near the top of the Rim Rock was selected for the first field experiment. It is overlain by shale and underlain by tight sandstone. Average characteristics of the section determined from analysis of 22 samples of core are given in Table 2. Average API gravity of the contained bitumen is about 10°, and the viscosity at reservoir temperature, 55° F., is greater than 500,000 centipoises.

The well pattern for the first experiment is shown on Figure 1. It consists of two rows of three air injection wells at either end of a rectangular area, 40 ft. wide by 120 ft. long. A row of three production wells is located across the center of the area. Thus, the injection wells and the production wells are spaced 20 ft. apart and there is 60 ft. between the injection and the production wells. Six temperature monitor holes are located within and adjacent to the well pattern as shown on Figure 1. This pattern provides a linear array of wells comprised of three elements each consisting of two air injection and one production well. The overall width of the array is 60 ft. The oil in place within the test zone under this array is calculated to be about 2200 barrels.

The production and injection wells were drilled to a depth 10 ft. above the estimated top of the test zone, and then cored to identify the top and bottom of the zone. Injection well casing (6 5/8-in.) and production well casing (7-in.) were set on top of the test zone and cemented, and the wells completed open hole. The temperature monitor holes were drilled through the test zone and completed with 1 1/2-in. pipe (bottom end plugged) set on bottom and cemented to the surface.

The production wells are equipped with two tubing strings: One (2-in.) to produce the hot vapors to the surface, and the other (1-in.) to transmit cooling water to the bottom of the wells. Thermocouples are attached near the bottom and about 75 ft. up on the 2-in. tubing to observe temperature and control injection of cooling water.

Air will be injected into the casing of the injection wells. Under the assumption that only about half of the injected air would reach the production wells, an optimum air flux (35 std. cu. ft./hr.-ft.) would require total injection rate into the six wells of 92,400 std. cu. ft./hr. The air will be provided from six air compressors, each with rated capacity of about 25,000 std. cu. ft./hr. at 250 lb./sq. in., and a booster with capacity of 96,000 std. cu. ft./hr. at 500 lb./sq. in.

<table>
<thead>
<tr>
<th>TABLE 2. AVERAGE PROPERTIES OF EXPERIMENTAL SECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitumen in place</td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>Porosity, percent</td>
</tr>
<tr>
<td>Permeability, millidarcy</td>
</tr>
<tr>
<td>Oil saturation, percent of pore volume</td>
</tr>
<tr>
<td>Oil saturation, percent by weight</td>
</tr>
<tr>
<td>Water saturation, percent of pore volume</td>
</tr>
</tbody>
</table>
Vapors produced from the three production wells may be as hot as 500° to 800° F. They will pass through a two-phase separator where, as a result of air cooling, some heavy components of the oil may be condensed and collected, then through a water-cooled heat exchanger for cooling to about 100° F. From the heat exchanger the fluids will enter a three-phase separator for separation of gas, oil, and water. Vapor from this separator will pass through an electrostatic precipitator for removal of oil mist, and then vented to the atmosphere through a stack. Produced oil and water will be pumped to storage tanks. Two complete separator facilities are provided to permit continuous production as well as independent flow testing of each production well.

Monitor and control of injection rates and of production well temperature and cooling water injection, and recording of associated data on gas production rate, cooling water temperature, and monitor well temperatures will be done with a mini-computer located on the site. The computer will also be used to compute heat and material balances for estimating the location of the combustion front and to correlate the results with temperatures in the monitor wells.

**PATTERN FLOW TEST AND INJECTION PROCEDURE**

Radio-tracer injection during stabilized air injection into all injection wells was made to determine the air injectivity and flow distribution of the test pattern. The radio-tracer (krypton 85) was injected into each injection well separately and then measured in the air production from each of the three production wells. The results of these tests are summarized in Figure 7. The large

**FIGURE 7.-AIR-FLOW DISTRIBUTION BY RADIO-TRACER.**
circles show location of the bottom of the producing wells, 1P1 to 1P3, and the relative proportion of the produced gas derived from particular injection wells. The next smaller circles show the location of the bottom of the injection wells, HI to 116. The small circles show the location on the surface of all wells, including the monitor holes, 1M1 to 1M6. The total air produced amounted to less than 28% of that injected; thus, most of the air is going outside the pattern. The direction of preferred flow appears to be northwest-southeast. Little of the air injected into wells 112 and 1X6 is produced in the pattern. Some anomalous relations are seen in the crossing of flow direction arrows, as shown by the rapid appearance (13 min.) of tracer in 1P2 from 113 and a corresponding production of tracer in 1P3 from 115. This has occurred during simultaneous injection into all injection wells.

Because of this observed flow distribution and the small overall return of injected air, ignition will be attempted by injecting air into production wells 1P2 and 1P3, instead of the air injection well, 1P1. A fuel pack of diesel-soaked charcoal placed in the open hole of 1P1 will be ignited by lowering a lighted fuse from the surface through the 2-in. tubing. During ignition, sufficient air will be injected to give a production rate from 1P1 of about 1,000 std. cu. ft./hr. After burning in the fuel pack is established, propane will be injected into the air injection manifold to provide a 1-percenfin-air mixture to 1P2 and 1P3. This ignition procedure was successfully used at Bellamy (9) to obtain ignition under reverse air flow conditions. Ignition in the forward direction resulted in almost immediate plugging of the formation. The propane mixture facilitates transfer of the combustion from the wellbore (fuel pack) into the formation.

After transfer of combustion to the formation is assured, injection in 1P2 and 1P3 will continue until the fire front reaches these wells. Then, air injection will be transferred completely to the injection wells to permit the front to move in that direction. Air will probably not be injected into 112 or 116, because of the poor air return experienced from injection into these wells.

It is probable that if a reverse combustion front can be established, that it will move in the preferred flow direction, or northwest-southeast. The degree of vertical and horizontal sweep that can be expected is not known. The properties of the zone from the core analyses were shown to vary appreciably across the pattern and from well to well. If an optimum air flux can be maintained, the front should move across the pattern in about 6 weeks. The maximum amount of oil that could be produced from this pattern is about 800 barrels, for a 75% sweep efficiency and a 50% recovery efficiency.

Ignition was attempted in the central production well on November 12, 1975, but was unsuccessful. Failure to ignite from lighted fuses dropped or lowered into the well is attributed to the charcoal fuel pack having become water-soaked due to condensation from the relatively warm air injected into the cold formation during the preceding injectivity tests. Clean-out of the well, preparatory to emplacement of a new fuel pack and an electric heater for the second ignition attempt, was in progress at the time this paper was presented.

LITERATURE CITED

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