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REPORT OF INVESTIGATIONS

FIELD EXPERIMENT OF REVERSE COMBUSTION OIL RECOVERY FROM A UTAH TAR SAND

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FIELD EXPERIMENT OF REVERSE COMBUSTION OIL RECOVERY FROM A UTAH TAR SAND

by

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ABSTRACT

A field experiment to recover oil from tar sand by reverse combustion was conducted at Northwest Asphalt Ridge, near Vernal, Utah. This test was in a 10-foot interval of the Rim Rock sandstone member of the Mesa Verde Formation at a depth of approximately 300 feet.

Ignition was accomplished November 25, 1975, and the reverse combustion front was propagated successfully through the formation. Results of the field experiment differed significantly from the results of laboratory tests that were used in the design of the field test. This difference is attributed primarily to the extreme heterogeneity of the tar sand formation.

Observed temperatures in the burned area were lower than expected, but a large portion of the tar sand within the pattern boundaries was heated to the extent that the bitumen became mobile enough to be produced. After 3½ weeks of operation, the project was terminated because of the inability of the surface production equipment to accommodate the heavy hydrocarbons being produced.

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Although the formation of the cracked products of reverse combustion was less than expected, this recovery process may be used successfully to heat the tar sand reservoir to a temperature high enough that the bitumen becomes mobile enough to be produced.

INTRODUCTION

The recovery of oil from tar sands in the United States has received only limited interest in the past. Recently, oil price increases and the decline of domestic oil reserves have made this source of energy more attractive. Deposits of tar sand are widely distributed throughout the U. S., but the most significant tar sand deposits are in the State of Utah. An efficient means of recovering oil from tar sands could increase the hydrocarbon reserves of this country by billions of barrels.

One area of research within the Laramie Energy Research Center of ERDA is devoted to development of methods for recovering oil from tar sands. In situ methods are of primary consideration since only a small portion of the tar sand resource is thought to be minable, and because of environmental concern. After a laboratory study using Utah tar sands (1),5/ the reverse combustion oil recovery process was selected for further investigation in a field test.

The reverse combustion process was designed to recover oil from formations containing very viscous or semi-solid hydrocarbons (2). This method differs from forward combustion in that the combustion front travels in the direction opposite to the direction of air flow. An advantage of the reverse combustion method is that the hydrocarbons flow with the combustion gases through the hot region of the reservoir. In

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5/Underlined numbers in parentheses refer to items in the list of references at the end of this report.

forward combustion, hot mobile oil can flow into the cooler region ahead of the front where it can congeal, plugging the formation to further flow. Another attractive feature of reverse combustion is that the original bitumen is cracked into a lighter oil as the combustion front passes through the formation. This oil remains in the vapor state while passing through the hot, previously burned zone.

The use of property owned by Sohio Oil Company at Northwest Asphalt Ridge, west of Vernal, Utah was obtained for the field experiment. A corehole was drilled on this property, and based on core analysis, an interval of tar sand appropriate for the field test was selected.

TAR SAND PROPERTIES

The tar sand zone selected for.the test is in the Rim Rock sandstone member of the Mesa Verde Formation, and is approximately 10 feet thick at a depth of 300 feet. The selection of the test zone was based on tar sand richness, effective permeability to air and the apparent isolation of the zone by impermeable layers above and below the zone. After selecting the test zone, a line drive pattern and five temperature monitor wells were drilled. The first corehole served as an additional monitor well.

The pattern consists of two rows of air injection wells spaced 60 feet on either side of a row of production wells. Each row contains three wells spaced 20 feet apart. These wells were cased with 7-inch casing set and cemented at the top of the test interval with open hole through the test interval. The production wells were completed with a string of 2-inch tubing and a string of 1-inch black pipe. The six temperature monitor wells were cased with 1½-inch pipe. Figure 1 shows the well

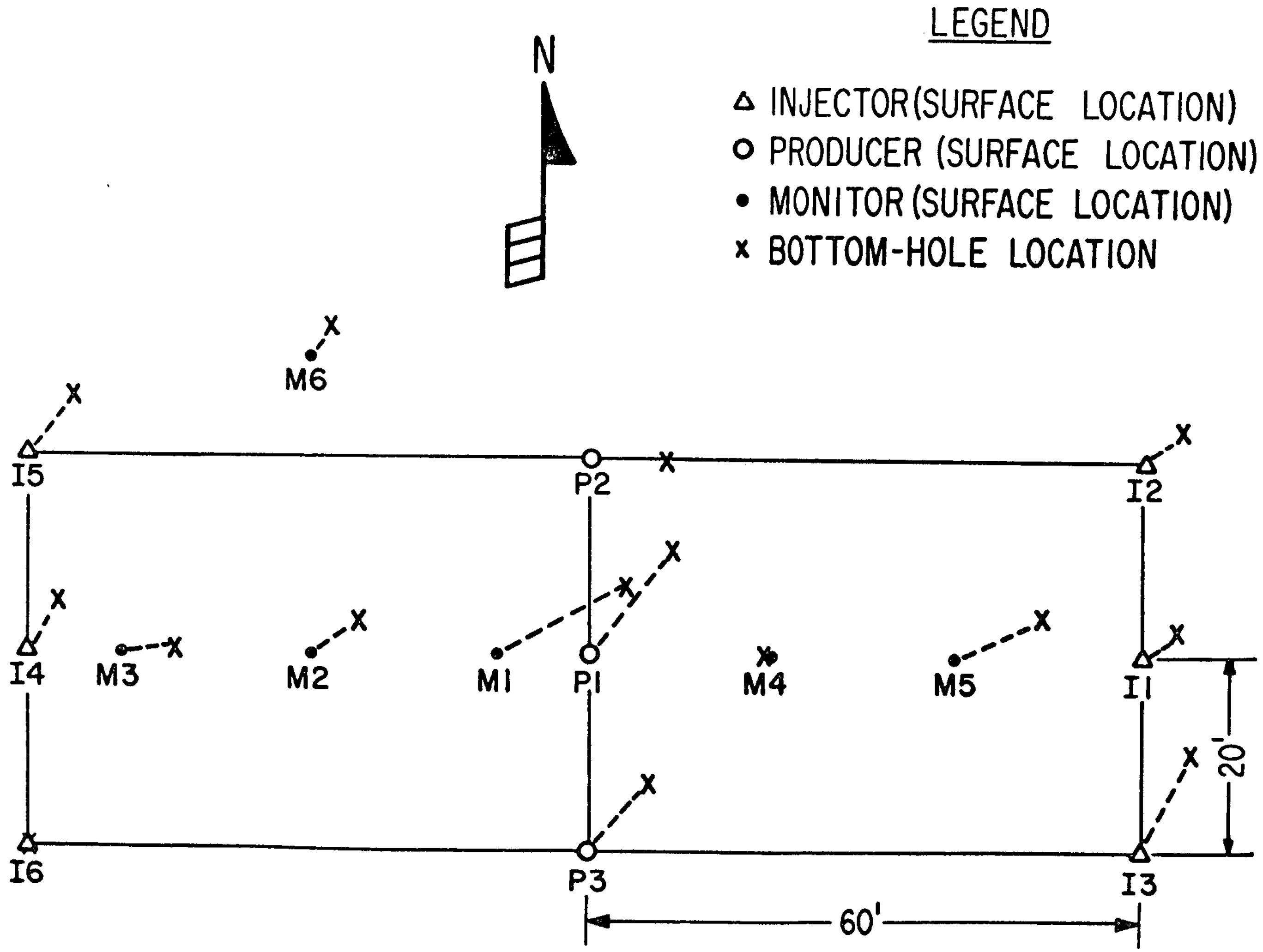

FIGURE 1 - Well pattern showing bottom hole location

configuration and bottom-hole locations of all 15 wells as determined by deviation surveys.

The test zone was cored in 14 of the 15 wells. The interval varies in thickness from 8 to 13 feet, with an average thickness of 10.4 feet. The top of the zone was picked at the contact of the tar sand with an overlying shale bed that ranged in thickness from less than 1 foot to 8 feet over the pattern area. Several tar sand stringers interbedded with shale lie above the shale marker. The bottom of the tar sand zone is in essence sealed by a limestone layer, approximately 1-foot thick, extending over the pattern area except at the southwest corner. A thick section of highly-saturated tar sand with very small effective gas permeability underlies the limestone. The top of the selected zone dips approximately 20 degrees in a general south-by-southwest direction.

Cores from 14 wells were analyzed for effective permeability to air, absolute permeability, porosity, and oil and water saturations. Average values of these properties are given in table 1. Effective gas permeability data exhibited a large variation. Permeability streaks could not be correlated between wells, although the distances are relatively short (a minimum of 6 feet between the bottoms of two wells). A plot of the effective gas permeability data shows a reasonable approximation to a log-normal permeability distribution, with the coefficient of permeability variation of 0.90[3]. The geometric mean effective gas permeability is 19 md, considerably less than the 182 md arithmetic mean of of the first core used to select the zone. In selecting the test zone, an effective gas permeability of at least 100 md was considered to be essential to maintain the desired air flux at reasonable injection pressure.

TABLE 1. - Average properties from core analysis

Porosity, percent	Effective gas permeability, md.	Absolute permeability, md.	Oil saturation, percent	Water saturation, percent
26.1	132	651	62.0	7.9

The average oil saturation of 0.62 and porosity of 0.261 correspond to 8.6 percent bitumen by weight. Viscosity of the bitumen at the reservoir temperature of 52° F is in excess of one million centipoise. Bitumen extracted from the core from the first well has an API gravity of 14.4, contains 0.59 percent sulfur and 1.02 percent nitrogen. This bitumen contains 31 percent wax, which has high concentration of cyclic paraffins with about 30 carbon atoms. Light-colored thin streaks were observed in most of the cores. Analysis of the material from one of the streaks proved the material to be 87.2 wax similar to that in the darker bitumen but the lighter material also contained normal paraffins in the C_{43}-C_{59} range.

AIR INJECTION TESTS

Prior to ignition, air injection tests were conducted to determine if the desired air flux could be maintained. It soon became apparent that the test zone would not take the desired rate of air injection at pressures less than 300 psig. Pressures in the injection wells were increased until pneumatic fracturing occurred at pressures ranging from 300 to 450 psig. The production wells were not fractured. Tracer studies indicated that the majority of the air flow was in the direction approximately parallel to the strike with very little flow along the dip of the formation (4). The northeast and southwest injection wells did not communicate with the line of production wells, and were not used during the field experiment. After the pneumatic fracturing, injection wells were capable of air injection at a rate of 16,000 scf/hr per well. Only about 25 percent of the injected air was produced from the row of production wells, and the rest was lost to the low-pressure region surrounding the pattern.

With injection into the two end production wells, air flow from the center production well was sufficient to initiate combustion and propagate the burning front from the center well several feet into the formation. A decision was made to ignite only the center well while injecting into the end production wells. Permeability was expected to increase in the burned region so that the flow rate could be increased to maintain the necessary air flux as the front burned away from the producing well. According to the plan, when the combustion front reached the two production wells used as injectors, these two wells were to be put on production and injection was to be started in the injection wells. This procedure was planned to provide a burned region along the line of producers for the dual purpose of increasing the permeability in the vicinity of the production wells and to obtain a more even advance of the combustion front toward the two rows of injection wells.

INSTRUMENTATION

A Hewlett-Packard 2100 computer with a disc-based real-time system was used for monitoring and control during the field experiment. The computer was programmed to read periodically thermocouple and pressure transducer outputs, store the data on the disc, perform data reduction, and print out various summary reports.

A thermocouple was installed in each temperature monitor well with an arrangement for raising and lowering the thermocouple through the tar sand zone. With this arrangement and with the aid of the computer, temperature as a function of depth was obtained with the option of plotting the data. Three thermocouples were installed in each production well; two were strapped to the 2-inch production tubing at positions 15 feet and 75 feet above the top of the zone, and the other was installed in the wellhead. Other thermocouples were placed in strategic positions in the production equipment and flow lines.

Air lines to each injection well were equipped with orifice meter runs, with pressure transducers to measure static pressures and pressure drops across the orifices. The computer used the outputs from the transducers to calculate flow rates to each injector and controlled the flow by outputting adjustments to an electrically operated control valve on each injection line. Orifice runs with pressure transducers were used also on the gas production lines to supply the computer with the data necessary to calculate the gas production rates.

Analysis of the produced gas were obtained with a gas chromatograph. The gas analysis equipment was interfaced with the computer, and the computer was programmed to sample the production gas, read the data, and calculate percentages of each gas component. However, due to malfunctions of the chromatographic equipment, requiring an unusual amount of manual adjustment, the computer control was not used.

The data acquisition and control system was entirely satisfactory, and the computer operated continuously throughout the field experiment without a failure.

OPERATION OF THE FIELD TEST

At the time of completion of the production wells, charcoal briquets were placed in the wells to fill the open hole to the casing shoe. Before attempting ignition in the center production well (P1), five gallons of diesel fuel were pumped in the well to soak the charcoal. Ignition of the charcoal by dropping lighted fuses was unsuccessful. On November 25, ignition was accomplished after lowering a 660-watt calrod heat on the bottom of the 1-inch tubing. After ignition, the electrical cable was pulled loose from the heater and removed from the well.

During ignition, the gas flow rate from the center well was 100 scf/hr. The production rate was increased gradually, and two hours after ignition the gas production rate was 1,440 scf/hr and the temperature at the lower thermocouple position was 428° F. About two hours after ignition, one percent by volume propane was mixed with the air being injected, and propane injection was continued for two days. Four days after ignition, the north injector (P2) was shut in, as it was thought that this well was contributing to combustion in the production well by flow of unreacted air through a burned-out fracture. Air injection was then started in four injection wells (11, 13, 14, and 15) in addition to the south production well (P3) still in use as an injector.

The gas production rate increased to 225 Mscf/day by December 4. By December 8, the gas production rate had dropped to 82 Mscf/day. This decline in flow rate is believed to be the result of partial plugging of the production tubing. The north production well (P2) was put on production in an attempt to increase air flux in the reservoir to maintain combustion. At this time, about 12 barrels of the cracked products of combustion had been produced. Production of bitumen began when the second well was put on production. Air was injected at approximately 1.5 MMscf/day during most of the test period at an average pressure of 425 psig. During the same period, the average daily gas production was 0.24 MMscf, indicating that 84 percent of the injected air was flowing out of the pattern. Casing pressure of the center producer was observed as high as 290 psig as the plugging of the tubing in this well became more severe.

On December 13, the burning front reached the south production well (P3) still in use as an injector; this well was put on production. Operation of the project was becoming increasingly more difficult because of the continued production of bitumen that had been only slightly altered by the combustion process. The surface production equipment was designed for the production of the cracked products of reverse combustion, a 22° API gravity crude oil. The bitumen being produced had a pour point of 175° F, and congealed in the oil and gas separator and production lines. Operation of the project was discontinued on December 19, after 23 days of operation. During the operation of the project, a total of 30.2 MMscf of air was injected with the cumulative gas production of 4.7 MMscf. Total liquid hydrocarbon production was 65 barrels, and water production was 167 barrels.

RESULTS

After ignition, the temperature of the center production well continued to increase for several days. Figure 2 is a plot of the temperatures sensed by the three thermocouples in this well. the peak temperatures of the lower thermocouple are thought to indicate burning of production in the well. Figure 3 shows the temperatures at the position of the lower thermocouple in the three producing wells. These temperatures are consistently higher than the temperatures observed in the monitor wells. A plot of the temperatures at the mid-point of the zone in the six monitor wells is shown in figure 4. In this plot, the maximum temperature observed is less than 300° F.

Typical temperature profiles obtained by raising the thermocouple through the tar sand interval of one of the monitor wells are illustrated in figure 5. In this well, the temperature of a relatively thin thickness of the zone rose for a period of three days. On the third day, the peak temperature of 246° F was reached. A peak temperature of 350° F was observed in another monitor well; this was the highest temperature observed in the tar sand zone during the field test. The temperature rise apparently resulted from the passage of a reverse combustion front through a thin high-permeability streak. The peak temperature then dropped, while the temperature above and below the thin burned zone increased more gradually until a temperature of 210° F extended across a 15-foot thickness of tar sand. The vertical position of the first temperature rise in each monitor well coincided with the position of the maximum effective gas permeability from core analysis. However, a single continuous high-permeability layer does not exist, as the relative vertical position of the maximum permeability is not the same in each well.

The rise in temperature was observed in four of the six monitor wells. Using the arrival times and the distance from the center producer, the average front velocities were calculated. These data are shown in table 2. In general, the calculated front velocities show the same directional trend that was observed in the tracer study. The front velocity in the direction parallel to the formation dip is less than the velocity along the strike.

The observed peak temperatures were lower than expected for the propagation of a reverse combustion front. From the results of laboratory experiments (1), temperatures in the range of 600-800° F were expected. The rate of the oxidation reaction is known to increase with pressure, resulting in lower combustion temperatures at higher pressures (5). However, such low temperatures are difficult to justify as being entirely due to the effect of pressure on reaction rate. After the elevated temperatures were established in a thin zone, the rise in temperature over the rest of the interval occurred as a result of oxidation at a slower rate where the air flux was small. A similar temperature history was observed in all four monitor wells within the burned region.

TABLE 2. - Average front velocities

Well	Time, days	Distance from P1, ft	Average velocity, ft/day
M1....	9	6	0.67
M2....	23	35	1.52
M4....	16	16	1.00
M5....	15	41	2.73
P3....	18	24	1.33

The average composition of the produced gas is given in table 3. From the average gas composition during the experiment, calculations show that 63.9 percent of the oxygen was used in combustion, 17.3 percent was unreacted, and the remaining 18.8 percent was assumed to be fixed to the hydrocarbon molecules as a result of partial oxidation of the bitumen. The oxygen being considered here is confined to that portion of the injected air contacting the pattern area and contributing to the combustion gas produced from the production wells.

TABLE 3. - Average gas analysis

Component	Percent
N_2......	79.9
CO_2......	9.5
CO	2.6
O_2......	2.9
H_2......	0.5
CH_4......	0.6

From the combustion products, calculations show that approximately 3×10^8 Btu of heat were generated in the reservoir. This quantity of heat is sufficient to heat 47,000 cubic feet of tar sand to 200° F. Based on this figure, times of arrival of the temperature rise in the monitor wells, and thickness of the heated zone observed in the monitor wells, the approximate extent of the heated area was determined. The area of heated tar sand is shown in figure 6.

SUMMARY AND CONCLUSIONS

The tar sand zone selected for the field test was extremely heterogeneous, and the mean gas effective permeability was less than desired to insure the optimum air flux. In addition, the effective gas permeability exhibited a directional trend. Because of these and other effects, 84 percent of the injected air was lost from the pattern. Under these adverse conditions it was still possible to ignite the tar sand and propagate a reverse combustion front through a thin section of the reservoir.

As a result of air injection, a large portion of the tar sand reservoir was heated to a temperature high enough to mobilize the bitumen. Although the limited production of the cracked products of reverse combustion was disappointing, the process was successful in heating the tar sand to a temperature at which the bitumen could be produced.

If the production equipment had been suitable to accommodate the production of bitumen and if the production tubing could have been kept free from plugging, continued injection of air would have resulted in a large fraction of the bitumen being recovered by the advance of a forward combustion front echoing from the injection wells.

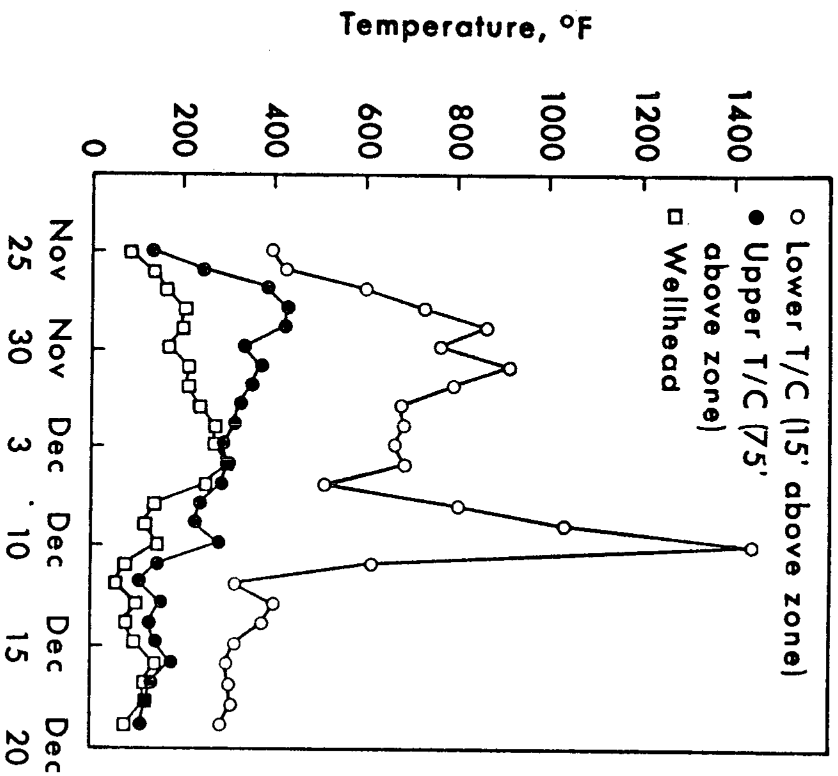

FIGURE 2 - Temperatures at three positions in the center production well, P1

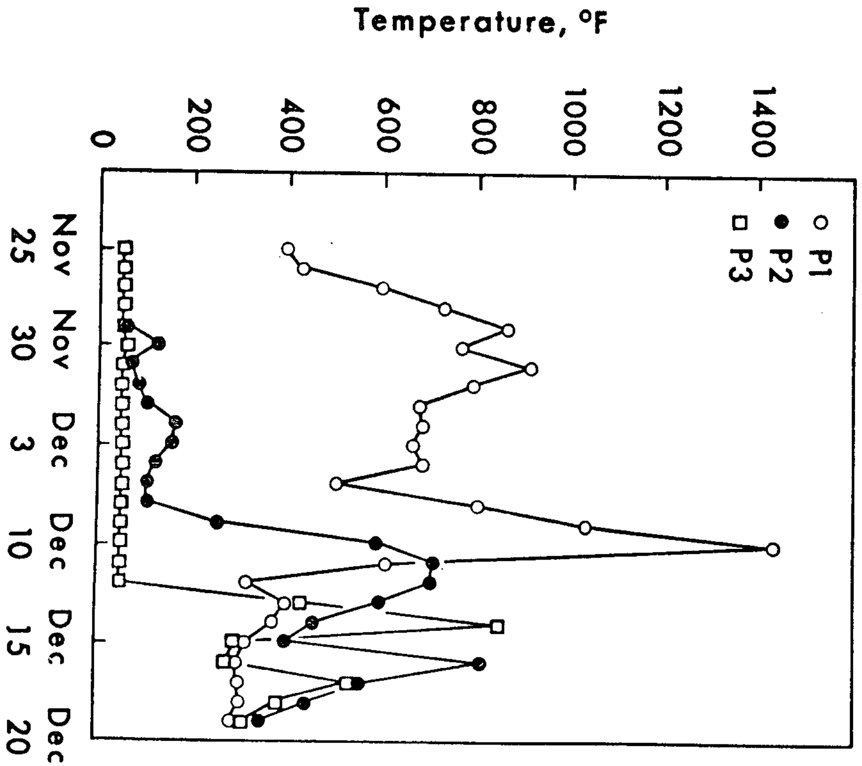

FIGURE 3 - Temperatures at the positions of the lower thermocouples in the three production wells

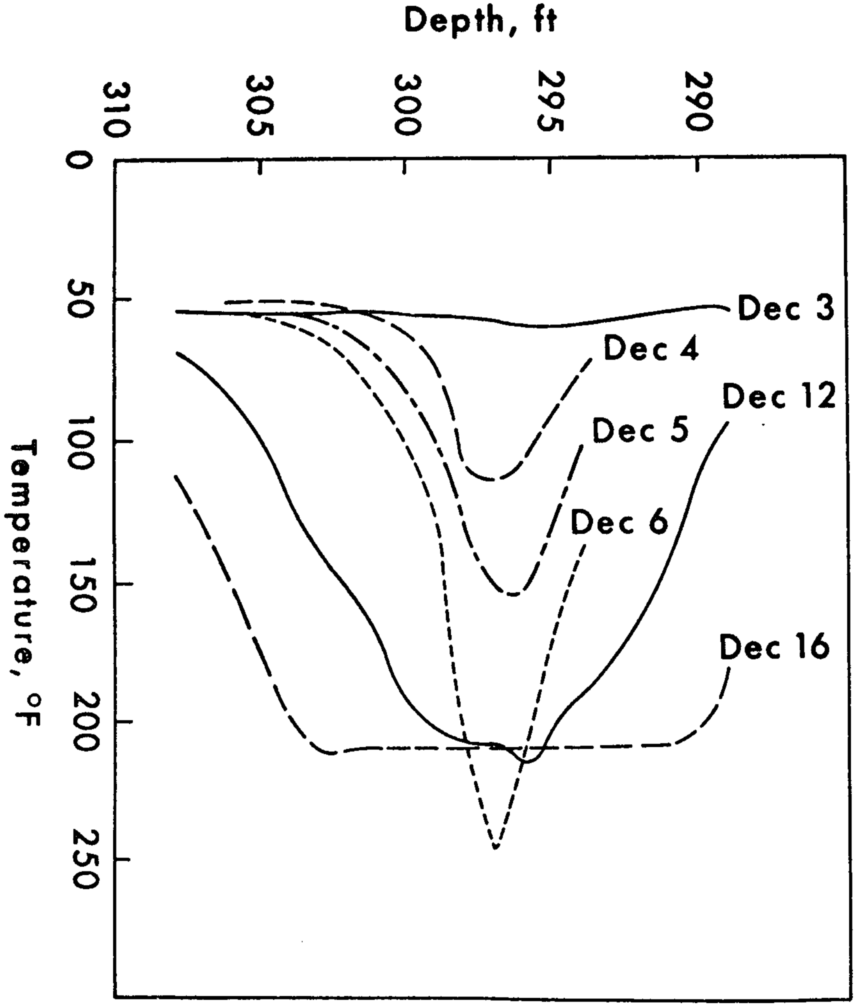

FIGURE 5 - Temperature profiles, monitor well 4

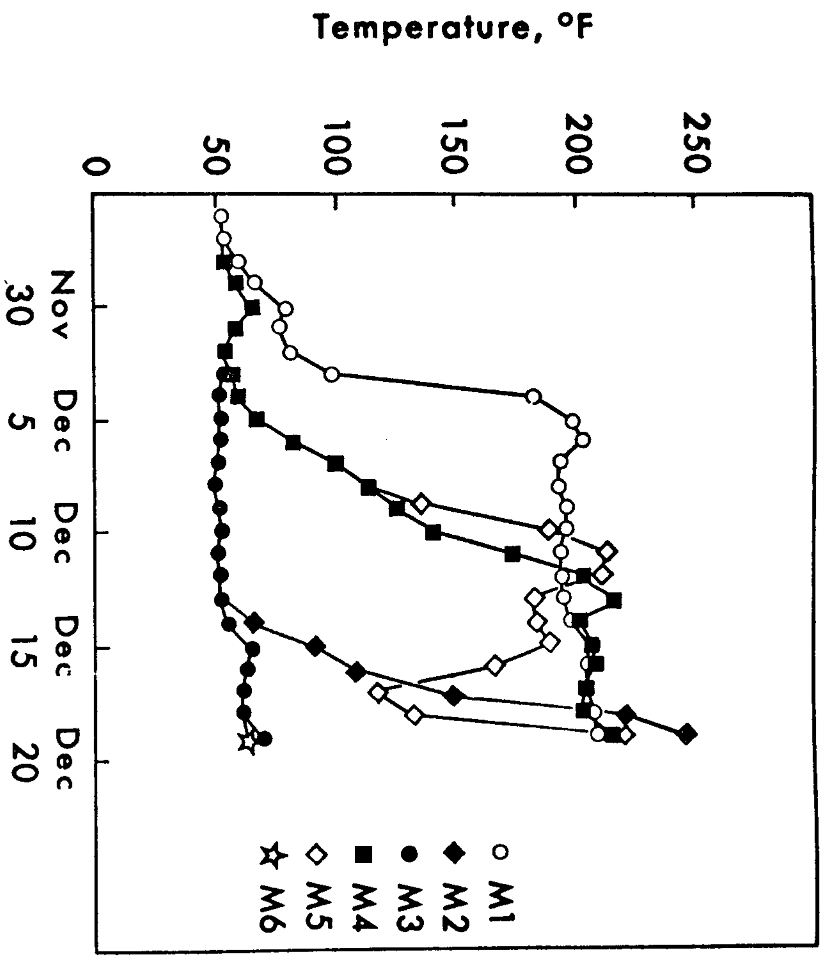

FIGURE 4 - Temperature histories at the mid-points of the tar sand interval of the temperature monitor wells

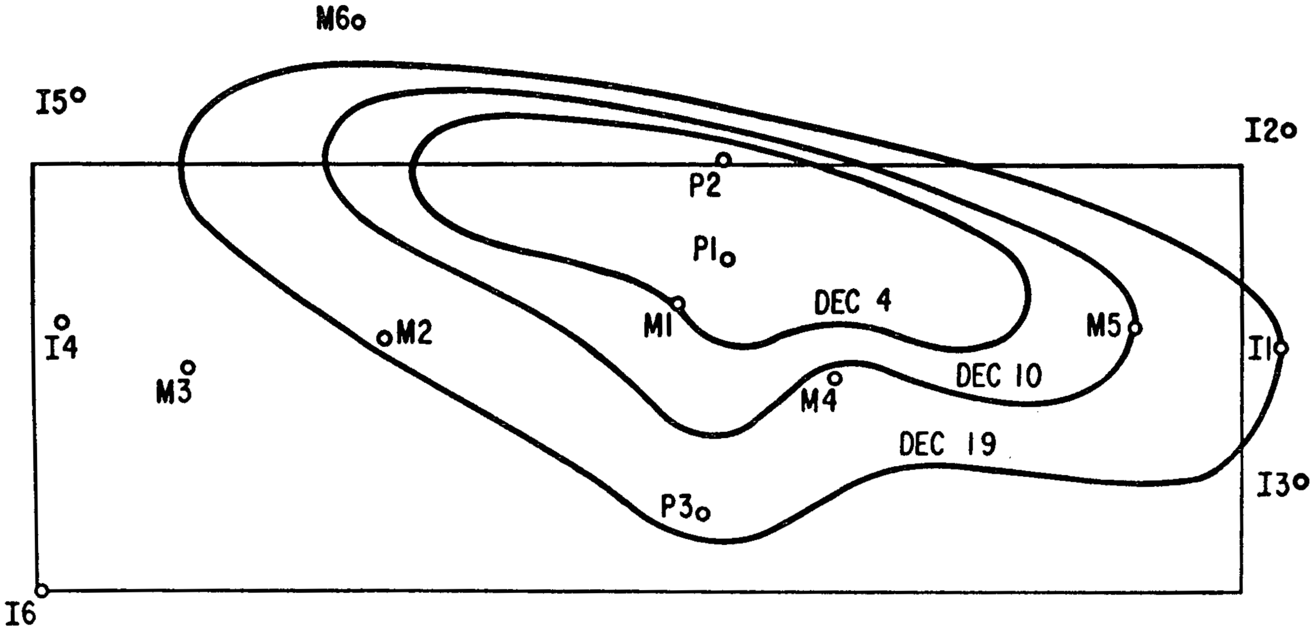

FIGURE 6 - Estimated areal extent of heated tar sand

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