AN EXPERIMENTAL STUDY OF FLOW MECHANISMS IN IN SITU OIL SHALE RETORTING

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ABSTRACT

A series of experiments were conducted to study fluid flow mechanisms during retorting of oil shale under simulated true in-situ conditions. Each test was performed by heating an enclosed core in a pressure vessel. One end of the core was open to production while the other end was completely sealed. A simulated overburden pressure of 1000 psig was used. The core was heated to the decomposition temperature of kerogen at an average rate of 35 degrees C per hour. An important flow phenomenon was identified.

An onset of kerogen decomposition gives rise to a rapid increase in pressure in the confined region of the oil shale. The pressure will rise to a maximum value, the magnitude of which depends on the shale grade. Immediately after the maximum has been reached, a very rapid decrease in the pressure in the confined region will occur. The decrease is usually accompanied by an equally rapid increase in temperature at the same location. This phenomenon is believed to be caused by a breakthrough in flow resistance which results in a sudden increase in the permeability of the shale. Such a change in permeability is very essential in determining the success of true in-situ oil shale retorting.

Typically, conducting realistic true in-situ oil shale experiments encounters many practical problems. The difficulties encountered in performing this series of experiments will be discussed. The effects of shale grade, core size and bedding plane orientation on the breakthrough phenomenon will also be presented.

INTRODUCTION

There are three principal methods for retorting oil shale: surface processing, in-situ methods and combination methods. True in-situ oil shale retorting remains the least known method. It has the advantages that the problems associated with surface processes like mining, crushing and handling of oil shale and disposing of spent shale do not exist. Important process parameters considered in in-situ retorting include type of heat source and means of heat transmission through the formation, factors affecting rate of kerogen decomposition and flow of oil out of the formation. The objective is to produce oil at a rate that yield losses in the retorting zone can be minimized.

A number of field trials were attempted during the past 30 years. Not all of the conceptually possible processes have been piloted. In-situ forward combustion was used in pilots operated by Sinclair (1) and USBM (2) while injection of hot gas (and later steam) was tried by Equity (3). Unfortunately, none of these was really successful. Only a fraction of Fischer Assay (FA) yield was obtained. The main problems were the lack of distributed fluid transmissibility and the actual blocking of fluid flow. Another concern is the effect of pressure. Oil shale deposits occur at depths of several thousand feet or lower. The retorting pressure may be high enough to affect both the kinetics of thermal decomposition of oil shale and the transmission of shale oil vapor. Some laboratory results (4) indicate that high pressure reduces oil yield significantly. This effect can be caused by oil coking and cracking losses brought about by increased residence time due to the presence of high back pressure. Coking not only reduces oil yield directly but also contributes to excessively high temperatures in the retorting zone leading to thermal decomposition of the rock matrix, increased heat losses and reduced thermal efficiency. To reduce such oil losses, oil must be removed from the hot zone quickly. Other studies of in-situ retorting include methods of heating (5) and numerical simulation (6).

Most of the field pilots were conducted in oil shale zones in which in-situ permeability was enhanced due to natural leaching of salt deposits by ground water, the presence of natural or artificial fractures or in-situ rubblization.

Assuming that heat can be introduced into the formation with subsequent conversion of kerogen into oil, the success of the retorting process depends significantly on how the oil can be produced under in-situ
conditions. This paper is an attempt to study product flow mechanisms in oil shale in which there is no fracture and in which no leaching has occurred — that is one with very low permeability. Previous studies have shown that in-situ oil shale permeability can be less than 0.00091 md. Experimental studies using large oil shale bricks were done at the Energy Technology Center (7); their results were not very encouraging. The tests described in this paper are similar to the simulated large shale slab experiment conducted by Needham et al (8), however, the objectives are different.

The basic assumptions of this study are that the formation can be heated without structural modification, that no fluid injection is implemented and that kerogen decomposition will occur effectively.

EXPERIMENTAL PROCEDURE

Simulating in-situ oil shale retorting requires some trial and error. The constraints of the experiments require that heat be transmitted into the core without modifying its structure, that it should be subjected to a reasonably high overburden pressure and, at the same time, that temperature, pressure and fluid flow can be monitored. The original design was to wrap the core with a 0.001 inch stainless steel sheet and seal the edges by welding. Such an approach was abandoned because of the difficulty in providing a close fit around the core.

Figure 1 shows the experimental retort used. An oil shale core of 1.5 inches diameter by 3 inches long was ground to fit inside a stainless steel core holder. The walls of the core holder were made of thin (0.010 inch) stainless steel sheet. This allowed the transmission of fluid pressure from outside the core holder to the core. The excessive expansion of oil shale of very high grade tended to burst the thin-walled core holder. Three stiffening rings were added to provide structural support for the core holder for use with rich shale. For lean shale these stiffening rings were found to be unnecessary. To avoid overheating the core during welding, specially designed end caps were used so that they could be welded at about an inch from the end of the core. The core holder was surrounded by two sets of cylindrical heaters and a heater on the bottom. The core holder-heater assembly was placed in a pressure vessel which was pressurized to 1000 psig by nitrogen. The annular space between the core holder and the walls of the pressure vessel was filled with perlite — an insulating material used to minimize heat losses.

Temperature changes in the core were monitored by thermocouples attached to the core surfaces. Pressure fluctuations generated due to retorting were measured by Validyne pressure transducers. Temperature and pressure data were recorded by an Esterline Angus PD2064 data logger. Digital data from the data logger were transmitted to a Hewlett Packard 9834T desk top computer and stored in a cassette. Real time data plotting was done by a HP9872B plotter.

Gas products were condensed by a glycol-cooled condenser. Oil mist beads the condenser was precipitated by an electrostatic precipitator. The gas production rate was measured by a wet test meter. Figure 2 shows a schematic of the set-up.

RESULTS

Five tests were conducted. The data from two of the tests (Run A and Run B) are presented. Interpretation and conclusions will be drawn from the results of all the tests. Shale core with a grade of 29.2 gallons per ton (gpt) was used in Run A. It was heated to 500 deg. C at an average rate of 40 deg. C/hr. In Run B, a core of 23.1 gpt was used. The average heating rate was 32 deg. C/hr. The major difference between the two runs was the difference in bedding planes. The direction of product flow while in Run B the bedding planes were perpendicular. A run summary of the two tests is given in Table 1.

Temperature profiles from thermocouples located at the top, center and bottom of the shale core for Run A are shown in Figure 3. The top temperature was deliberately maintained at a lower level than the bottom temperature to prevent early generation of product gases. An average heating rate of 40 deg. C/hr was used. The change in pressure at the plugged end of the core is shown in Figure 4. Below 200 deg. C, the rise in pressure was slow. This slow increase in pressure was probably due to the liberation of water vapor and carbon dioxide. The maximum rate of increase occurred at temperatures between 300 and 400 deg. C, corresponding to the onset of kerogen decomposition. At 428 deg. C, a peak pressure of 289 psig was recorded. It was immediately followed by a rapid decrease in pressure. This decrease was accompanied by an equally rapid increase in temperature at the same location as shown in Figure 3. This phenomenon is believed to be caused by
CYLINDRICAL HEATER

TO PRESSURE TRANSDUCER

THERMOCOUPLE

SHALE CORE

THERMOCOUPLE

TO PRESSURE TRANSDUCER

CYLINDRICAL HEATER

BOTTOM HEATER

RETORT PRODUCTS

FIGURE 1: TRUE IN-SITU EXPERIMENTAL RETORT

FIGURE 2: BLOCK DIAGRAM OF TRUE IN-SITU EXPERIMENTAL SET-UP
### TABLE 1
#### RUN SUMMARY

<table>
<thead>
<tr>
<th>Run</th>
<th>Size</th>
<th>Bedding Grade</th>
<th>Overburden Pressure</th>
<th>Avg. Heating Rate</th>
<th>Maximum Temp.</th>
<th>Maximum Pressure</th>
<th>Gas Produced SFA</th>
<th>Oil Produced SFA</th>
<th>Raw Shale gm</th>
<th>Spent Shale gm</th>
<th>Spent Perm. md</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.50 X 3L</td>
<td>Parallel 20.2</td>
<td>1000</td>
<td>40</td>
<td>500</td>
<td>289</td>
<td>91</td>
<td>89</td>
<td>196.9</td>
<td>181.5</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>1.50 X 3L</td>
<td>Perpendicular 23.1</td>
<td>1000</td>
<td>32</td>
<td>500</td>
<td>735</td>
<td>73</td>
<td>74</td>
<td>197.2</td>
<td>180.9</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### TABLE 2
#### ANALYSIS OF OIL SHALE SAMPLES

<table>
<thead>
<tr>
<th>Sources</th>
<th>Specific Gravity 60°F/80°F</th>
<th>Gravity °API</th>
<th>Pour Point ºF</th>
<th>Viscosity cS, 100°F</th>
<th>C wts%</th>
<th>H wts%</th>
<th>N Atomic Ratio wts%</th>
<th>S wts%</th>
<th>IR 990/1375</th>
<th>IR 910/1375</th>
</tr>
</thead>
<tbody>
<tr>
<td>LURGI RUHRGAS</td>
<td>0.9120</td>
<td>23.7</td>
<td>64</td>
<td>17.5</td>
<td>85.90</td>
<td>11.10</td>
<td>1.55</td>
<td>1.72</td>
<td>0.75</td>
<td>NA</td>
</tr>
<tr>
<td>OXY MIS</td>
<td>0.9190</td>
<td>22.5</td>
<td>70</td>
<td>13.1</td>
<td>84.86</td>
<td>11.80</td>
<td>1.67</td>
<td>1.50</td>
<td>0.71</td>
<td>NA</td>
</tr>
<tr>
<td>RUN A</td>
<td>0.8897</td>
<td>27.43</td>
<td>NA</td>
<td>5.44*</td>
<td>84.03</td>
<td>11.88</td>
<td>1.70</td>
<td>1.96</td>
<td>NA</td>
<td>0.048</td>
</tr>
<tr>
<td>RUN B</td>
<td>0.8988</td>
<td>25.82</td>
<td>NA</td>
<td>10.52*</td>
<td>82.90</td>
<td>11.81</td>
<td>1.71</td>
<td>NA</td>
<td>NA</td>
<td>0.029</td>
</tr>
</tbody>
</table>

*Measurements were made with free water present in samples.
FIGURE 3: TEMPERATURE PROFILES OF RUN A

FIGURE 4: CONFINED PRESSURE OF RUN A
a breakthrough in the permeability of the core. We shall call the maximum pressure the breakthrough pressure. The occurrence of this breakthrough phenomenon resulted in an increase in the rate of oil and gas production. A high FA oil yield of 89% was obtained. The shows that almost complete retorting could have occurred with little oil degradation.

If the breakthrough phenomenon is a function of shale permeability, a change in bedding plane orientation will have an important consequence. Run B was designed to study this effect by using a core with perpendicular bedding plane orientation. The core had a grade of 23.1 gpt. Figure 5 shows the temperature profiles for the run. The core was heated at an average heating rate of 3 deg. C/hr. The change in temperature at the top (the plugged end) was highly irregular after the core temperature reached 150 deg. C. A possible cause of the anomalous cooling effect might be the condensation of water in the pressure tubing in which the thermocouple was enclosed.

The change in pressure at the plugged end is shown in Figure 6. This is similar to Figure 4 of Run A. Slow rate of pressure increase was observed at temperatures below 200 deg. C. Between 300 and 400 deg. C there was a rapid rise in pressure as happened in Run A. In this case a much higher peak pressure was obtained -- 735 psig. It occurred at 390 deg. C. It could have occurred at a higher temperature if the heating rate of the top heater had not been turned down temporarily. Again the rapid decrease in pressure was accompanied by a rapid increase in temperature -- a manifestation of the breakthrough phenomenon. A gas production history for Run B is shown in Figure 7. Maximum gas production rate occurred at temperatures between 375 and 430 deg. C. Breakthrough occurred at a temperature in approximately the middle of this temperature range. The corresponding oil production history is shown in Figure 8. Maximum oil production rate was observed at temperatures between 425 and 460 deg. C. Due to high oil viscosity and relatively large volume of dead space inside the tube in which oil flowed, the correct temperature range should have been lower. Total gas and oil productions were 73% FA and 74% FA respectively. Results of analysis of a number of oil samples are shown in Table 2. Data from Lurgi Ruhrgas and Oxy MIS shale oils are included for comparison. Burnham (9) found that oil yield loss due to coking increases as H/C atomic ratio increases. The higher H/C atomic ratio of oil from Run B indicates higher coking loss. Using correlation results of IR absorbance analysis given by Evans and Campbell (10), the lower value of IR absorbance ratio for Run B also indicates coking loss.

Examinations of the spent shale from both runs revealed the presence of microfractures formed perpendicular to the bedding planes. These microfractures are believed to be important in facilitating product flow. The permeability of the spent shale from Run B was found to be an order of magnitude lower than that from Run A, approximately 0.1 md versus 1 md. Pictures of the coreholders taken after the runs are shown in Figure 9.

In another run, Run C, a core with a shale grade of 29 gpt was used. The results showed that breakthrough phenomenon similar to that detected in Run A and Run B could be observed. The data were not analyzed in detail because of inaccuracy caused by a minor leak which occurred in the middle of the run.

A six-inch core of very low grade (14 gpt) was used in Run D. This core was twice the length of cores used in previous runs. This longer core gave rise to a very high breakthrough pressure of 851 psig. A comparatively low oil yield of 70% FA was obtained. Spent shale analysis showed that very little kerogen was left in the shale. Similar to previous runs, coking could account for most of the yield loss.

In another run, Run E, a core of very high grade (over 40 gpt) and 6 inches long was used. As the core was being heated to about 300 deg. C, the coreholder was burst open. Very high pressure in excess of 1000 psig could have been generated due to thermal expansion of the core.

CONCLUSIONS

Oil shale retorting and product release under high confining pressure appear to be feasible under the stated test conditions. The direction of product flow through the shale seems to have a significant effect on product yields. Flow in a direction parallel to the bedding planes gave much higher yields than in the perpendicular direction.

The higher coefficient of expansion of rich oil shale (due to the higher concentration of kerogen present in the rock) gave rise to lower permeability for product flow, thus making it unsuitable for true in-situ retorting. Product release from the rock matrix appears to occur by a phenomenon of pressure buildup of sufficient magnitude to cause a fluid flow breakthrough in the matrix.
FIGURE 5: TEMPERATURE PROFILES OF RUN B

FIGURE 6: CONFINED PRESSURE OF RUN B
**Figure 7:** Gas production during Run B

**Figure 8:** Oil production during Run B
FIGURE 9: STAINLESS STEEL CORE HOLDERS AFTER RETORTING FOR RUNS A AND B
Using the limited amount of data analyzed, it is remarked that, while it is uneconomical to retort lean oil shale by surface processes, such oil shale is more amenable to true in-situ retorting than rich oil shale. The concept of retorting rich oil shale by surface processes and rubblized lean shale underground has been made use of in modified in-situ technology.

The important parameters in in-situ oil shale retorting are shale grade, block size, bedding plane orientation, heating rate and overburden pressure. Fundamental studies of these parameters on product flow mechanisms and oil yield are needed to assess any potential application of true in-situ retorting.

LIST OF REFERENCES


