Analysis of Applicability of Oil Shale for in situ Conversion

Sergey Martemyanov[a)], Andrey Bukharkin[b)], Ilya Koryashov[c)] and Alexey Ivanov[d)]

Tomsk Polytechnic University, 30 Lenina Avenue, Tomsk 634050 Russian Federation

[a)] corresponding author: martemyanov@tpu.ru
[b)] amplexor@ya.ru
[c)] korish_nv@mail.ru
[d)] lexxdelphi@mail.ru

Abstract. There are only a few substantial oil shale industries in the world, mainly because of the high cost of oil shale development relative to coal, oil and natural gas. Innovative approaches to oil shale processing could change this situation. Underground (or *in situ*) conversion could become a very useful technology, once an efficient way is found to prepare oil shale deposits for heating and to transfer heat into them. A new electrophysical method, which uses electrical treeing breakdown and resistive heating to fracture and heat underground formations, appears to have great potential in this regard. This paper examines the potential applicability of the process to two oil shale deposits in Russia. Results of laboratory tests are presented that confirm the technology's ability to obtain high yields of good quality oil and gas. Values for some of the technology's important operating parameters are suggested, and energy ratios are calculated from both theory and results of the laboratory tests. The energy ratios of the process are compared with other methods of underground and aboveground oil shale processing.

INTRODUCTION

Oil shale is the most suitable solid fossil fuel for pyrolytic conversion. Its low degree of metamorphism promotes a high content of hydrogen in the kerogen – the organic component of the rock – which facilitates conversion to oil and gas.

The traditional method for developing oil shale is to mine the ore and heat it in aboveground vessels (retorts) to decompose the kerogen and produce oil and gas. This approach is very expensive, and it has serious environmental effects. In situ pyrolytic conversion is a promising alternative with high potential to reduce both costs and impacts. In *in situ* pyrolytic conversion, the oil shale rock is heated *in situ* (in place) to 400-600°C in an oxygen-free atmosphere. This heating generates a mixture of liquid and gaseous products, which can be used as raw materials for production of fuels and chemicals. The pyrolytic gas is a mixture of combustible components such as hydrogen, carbon monoxide and methane. The liquid product – shale oil – is a mixture of heavy hydrocarbons and is close in composition to natural crude oil.

A few different approaches to heating subterranean oil shale formations have been suggested by researchers [1-5]. In *in situ* combustion [1, 2], a portion of the deposit is set on fire, and the heat of combustion is transferred from the fire front to the rest of the deposit, causing pyrolysis of the kerogen and release of oil and gas. The main advantages of this technology are that no mining is required and all energy required for retorting is produced by burning a small portion of the oil shale. A big disadvantage is the high concentration of carbon dioxide in the product gas, which results in low calorific value.

Another approach has been suggested by ExxonMobil [3, 4]. Their Electrofrac process consists of hydraulically fracturing the deposit and filling the fractures with electrically conductive material, which forms a heating element. Passing electricity through the conductive material heats the surrounding formation and releases the oil and gas, which can be extracted through the fractures. The method does produce gas with high calorific value, but it requires many preliminary operations, such as horizontal drilling and hydraulic fracturing.

In Shell Oil Company's In-situ Conversion Process (ICP), an oil shale formation is heated with resistive heaters suspended in a ring of wells, and the pyrolytic oil and gas are extracted through a production well in the

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center of the ring [5]. The oil and gas have good quality, but, because of the low thermal conductivity of oil shale, heating a significant volume of oil shale requires many wells with many heaters and long heating times.

Our group aims to develop a simpler and more effective method of *in situ* conversion by using electrophysical heating (electrical treeing, breakdown and resistive heating) to fracture and heat underground formations. This method does not require hydraulic fracturing, with its significant time and capital investments, and it allows obtaining high-calorific products. The article presents results of initial laboratory tests and considers the energy efficiency of *in situ* pyrolysis conversion by electrophysical heating for oil shale of two deposits. Technological parameters of the suggested heating mode are described.

DMITRIEVSKY AND KOTSEBINSKY DEPOSITS OF OIL SHALE

The study used oil shale from two deposits – Dmitrievsky and Kotsebinsky – because they are slightly removed from towns and lie at shallow depth. The Dmitrievsky deposit is in the Barzas coal-bearing area in Kuzbass, Russia. The deposit has a thickness from 20 to 55 m, and the proven oil shale reserves are 132 million tons. The oil shale is of the lime-clayey type with long-flame stage of coalification. Ash content is about 70-75%. The organic component is low in sulphur (less than 0.2%), and the yield of semi-coking tar is high. The light and medium fractions of the tar are suitable for processing into commercial hydrocarbon products. The deposit is located in 20 km from Kemerovo [6].

The Kotsebinsky deposit of oil shale is part of the Perelyub-Blagodatovsky shale area in the Perelyubsky district of Russia's Saratov region. Reserves are 525 million tons. Average ash content is 65-70%. Bed top lies at a depth from 0.8 to 15.8 m. The shale-bearing series has a thickness from 28.6 to 37.6 m with interlayers of inert mineral rocks having a total thickness of 7.2-10.8 m. The oil shale layers are from 0.7 to 1.2 m thick. The deposit runs to 2.5 km in width and 12.5 km in length. It is located near Perelyub village, 362 km from Saratov [7].

OVERVIEW OF THE ELECTROPHYSICAL METHOD

The pyrolytic conversion of oil shale has long been regarded as a highly efficient technology for producing fuel gas and synthetic crude oil [8, 9, 10]. The opportunity to conduct pyrolytic processing *in situ* is a substantial improvement over traditional aboveground methods. Its advantages include:

- No underground or opencast mine must be constructed, so costs are reduced;
- No landscape violation occurs, because the strength of the pyrolyzed oil shale prevents land subsidence; and
- Products can be obtained directly from the liquid or gaseous energy carriers and converted into fuels and chemicals.

The most important technical requirement for *in situ* conversion is heating the formation to the temperatures where thermal degradation occurs. The authors believe an electrophysical method comprising the passage of electric current through the rock is the most suitable heating method [11, 12]. This method requires that two wells, positioned some distance from each other, be drilled from the surface into the formation. An electrode is placed in each well, and the electrodes are connected by cables to a supply of electric power with adjustable current. Heat is generated when a current is passed between the electrodes through the formation, due to the ohmic resistance of the rock. This energy heats the formation.

TREEING BREAKDOWN OF OIL SHALE

Solid fuels are materials with low electric conductivity; therefore, in their natural state, their direct heating by the passage of electric current is impossible. To allow such heating to occur, a channel of electrical breakdown must be created through the formation. The electrical treeing phenomenon is a good way to achieve electrical breakdown, because it can be induced at relatively low voltage [13]. A technically achievable voltage can be used to create an electrical breakdown channel between wells placed several tens of meters from each other.

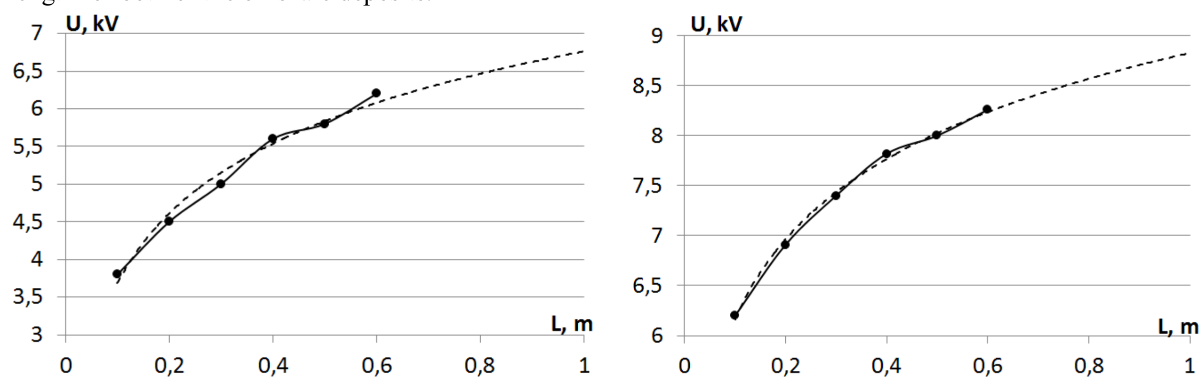
Further, the breakdown channel can be used as an electric heater, releasing heat energy to spread through the formation. With this approach, the heat energy can be generated not only in the vicinity of wells, but also in the whole area between the electrodes. This allows heating a larger rock volume, increasing the efficiency of the technology.

Because the breakdown of the inter-electrode gap precedes the heating of the subterranean formation, the voltage required to form the breakdown channel must be determined. Figure 1 shows the dependence of breakdown voltage on distance for Dmitrievsky and Kotsebinsky oil shale at a frequency of 50 Hz. Curves were developed from data obtained in the laboratory and then were extrapolated into the region of larger inter-electrode distances.

Laboratory measurements were made up to an inter-electrode distance of 0.6 m, and curves were extrapolated based on a logarithmic law. Logarithmic approximation was used because the voltage between discharge structures has a logarithmic dependence on the distance between the structures [14]. The curves indicated that achieving breakdown for a distance of 15 m requires a voltage of 13 kV for Dmitrievsky deposit shales and 16 kV for Kotsebinsky deposit shales. Such voltages are readily available from typical transmission lines.

Consumption of electricity should also not be a problem. Suppose the pilot unit for a full-scale test of the technology has a 15 m distance between electrodes. Experimental studies have shown that the specific power of a unit to heat a subterranean formation should be 1.5-2 kW per meter of length of the inter-electrode gap. For an inter-electrode distance of 15 m, the required power is not more than 30 kW. This amount of power can easily be obtained in field conditions from any local power line or produced with a liquid fuel generator.

A pilot unit will use for breakdown a high-voltage single phase commercially available transformer IOM-100/100 with an output voltage up to 100 kV. This voltage is sufficient to form a conductive channel of 15 m length for both of the oil shale deposits.



(a) (b)

FIGURE 1. Dependence of the breakdown voltage on the distance (firm line) and their logarithmic approximation with extrapolation (dashed line) for Dmitrievsky (a) and Kotsebinsky (b) oil shale.

After forming the conductive breakdown channel between the electrodes, the unit will switch from a high-voltage transformer to a high-current regulator, which will put heating energy into the breakdown channel and use it as a resistive heater to heat the formation. Heating will cause pyrolytic decomposition of the kerogen and synthesis of combustible gases and shale oil.

ENERGY EFFICIENCY OF THE ELECTROPHYSICAL PROCESS

The effectiveness of a conversion technology can be estimated by performing an energy balance for the conversion reaction and calculating the technology's energy efficiency – the ratio of energy produced to energy spent. For the electrophysical process, the energy balance was first estimated theoretically to determine the maximum achievable value. Then, experimental verification of the estimate was carried out.

According to thermogravimetric analyses, the best temperature range for oil shale conversion is 400-500°C [15]. Energy is expended to heat the rock to these temperatures and to produce the chemical conversion reactions. The amount of energy required to heat the rock depends on its effective heat capacity. Although heat capacity varies with temperature, using an average value should be sufficient. The average heat capacity of oil shale and similar minerals, according to the literature, is 1000-1200 J/kg·°C [16, 17]. Thus, the conversion of one kilogram of oil shale by heating from 20°C to 600°C needs the energy:

$$1200[J/kg\cdot°C]\cdot 580[°C] = 696000[J/kg] = 696[kJ/kg].$$

The energy produced by the process can be estimated from the heat of combustion of the gas and shale oil. The relative quantities of oil and gas produced depend on the heating conditions. Experimental data and the results of thermogravimetric analysis showed that 1 kg of oil shale with ash content of about 70%, such as Kotsebinsky and Dmitrievsky, can give about 140 grams of shale oil and the same amount of gas. These unusually high yields are a benefit of the electrophysical process. They are obtained from three sources: volatilization of the small quantity of bitumen in the oil shale, thermal decomposition of the kerogen, and thermal cracking of the carbonaceous residue from kerogen decomposition.

The specific heat of combustion heat of the shale oil is about 30000 kJ/kg. So burning the 140 g of recovered oil will produce:

$$0{,}14[kg]\cdot 30000[kJ/kg]=4200[kJ]\,.$$

The molar density of the produced gas is about 15 g/mole; so the volumetric density of the gas at atmospheric pressure is:

$$\frac{15[g/mole]}{22{,}4[l/mole]}\cong 0{,}7[g/l]=700[g/m^3]\,.$$

The volume of the 140 g of produced gas is:

$$\frac{140[g]}{700[g/m^3]}=0{,}2[m^3]\,.$$

The specific heat of combustion of this gas is about 13000 kJ/m^3. So burning the produced gas will release:

$$13000[kJ/m^3]\cdot 0{,}2[m^3]=2600[kJ]$$

The total calorific value of the conversion products is 6800 kJ, which is 9.7 times the heat energy required to produce the fuels. However the heat energy was obtained from electricity, and it is proper to account for the energy required to produce that electricity. If we suppose that fuels are converted into electricity with an efficiency of 35%, the energy conversion efficiency of the electrophysical process is reduced from 9.7 to about 3.4.

EXPERIMENTAL STUDIES OF THE ELECTROPHYSICAL PROCESS

Experimental testing of the electrophysical process was carried out on a small scale under laboratory conditions simulating an *in situ* environment [18]. The experiments used oil shale samples with dimensions 350×200×150 mm and weighing about 20 kg. The distance between electrodes was 300 mm.

A sample with embedded electrodes was placed in a sealed chamber. The electrodes were connected to an external source of electric power, and the flow of current was initiated. Electricity consumption was measured using a supply meter. The volume of produced gas was measured with a gas flow meter, and gas composition was determined by gas chromatography. The exact amount of produced shale oil could not be directly determined, because the aerosol particles of oil accumulated as a thin layer on the chamber walls. So oil production was estimated indirectly as the loss of weight of the sample minus the weight of the produced gas. The specific combustion heat of the shale oil was measured in a bomb calorimeter. Composition of the product gas is shown in Table 1. The other main results of the experiments are summarized in Table 2.

TABLE 1. Composition of pyrolysis gas from Dmitrievsky and Kotsebinsky oil shales

Component	Dmitrievsky oil shale	Kotsebinsky oil shale
H_2	46,2	53,8
CO	28,3	24,1
CH_4	9,2	8,9
CO_2	14,4	11,7
C_2H_6	0,9	0,8
C_3H_8	0,6	0,4
Specific combustion heat, kJ/m^3	12 999	12 932

Similar results were obtained for the two deposits, perhaps because the concentrations and compositions of the organic matter were similar and the samples were heated in a similar manner.

The energy ratio of conversion measured in the laboratory was only 3.2-3.3 instead of theoretically obtained value of 9.7. This difference may have been caused by several factors. Firstly, the rocks could not be heated evenly, leading to overheating or underheating of some areas, which would reduce the conversion efficiency. Secondly, the laboratory's universal electrical equipment was made with a large power margin, and therefore had a low efficiency of about 50%. An industrial unit that would be used in the field might have an efficiency of at least 90%.

Heating is clearly the main energy consumer in the proposed process. The only other activity that will consume significant amounts of energy is the drilling of two wells for the electrodes. Therefore, the values of energy efficiency measured for the heating stage should be close to the net energy ratio for the overall conversion process.

In situ conversion does seem to be a more efficient user of energy than aboveground conversion, especially when electrophysical heating is employed. For example, the calculated net energy ratios reported for retorting of

Green River oil shale in the aboveground Alberta Taciuk Processor are 1.8 and 1.1 for low case and high case respectively [19]. (Green River oil shale is similar to oil shale in the Dmitrievsky and Kotsebinsky deposits.) These results account for the energy requirements of all stages in the process, such as mining, transport, crushing, retorting, and so on. For comparison, reported values for underground conversion using Shell's ICP technology are 2.5 and 1.6 for the low and high cases respectively [20]. So the ICP method is more energy efficient than aboveground processing, and electrophysical conversion, with a conversion ratio of 3.4, is more energy efficient than ICP.

TABLE 2. Results of the laboratory heating of oil shale

Parameter	Dmitrievsky oil shale	Kotsebinsky oil shale
Time of heating, h	19	18
Average power, kW	0,585	0,593
Spent energy, kW·h / kJ	11,1 / 39 960	10,7 / 38 520
Volume of produced gas, m^3	5,5	6,3
Combustion heat of produced gas, kJ	71 490	81 470
Weight of produced shale oil, kg	1,82	1,51
Specific combustion heat of shale oil, kJ/kg	31 200	29 700
Combustion heat of produced shale oil, kJ	56 780	44 850
Energy ratio	3,21	3,28

SUMMARY

In situ oil shale conversion allows obtaining more net energy than aboveground processing. It also requires less capital investment because there is no need for mining or ash disposal. For *in situ* technologies to attain their maximum energy efficiency, they must achieve uniform heating of the subterranean formations. Heating by the resistive loss technique is most suited to achieving this uniform heating.

A simple method for calculating energy ratios can be used to estimate the conversion efficiency of a process when applied to a specific oil shale deposit. When the method was used in this study, substantial energy gains were predicted, and these were confirmed qualitatively by laboratory experiments. If employed at a properly chosen scale, the *in situ* conversion of oil shale by electrophysical processing could be both technically possible and profitable. The method should be useful for underground conversion of oil shale in many deposits with similar characteristics.

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