ExxonMobil’s Electrofrac™ Process for In Situ Oil Shale Conversion

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ABSTRACT: ExxonMobil’s Electrofrac process is an energy-efficient method for converting oil shale to producible oil and gas. The method heats the oil shale in situ by hydraulically fracturing the oil shale and filling the fracture with electrically conductive material, forming a heating element. The shale oil and gas are produced by conventional methods.

Electrofrac research has included small-scale experiments, numerical modeling, and resource description work addressing critical technical issues. This paper provides an overview of the research, highlights of which are listed below.

• Laboratory experiments demonstrating the following.
  ❏ Hydrocarbons will be expelled from heated oil shale even under in situ stress.
  ❏ Electrical continuity of the fracture heating element is unaffected by kerogen conversion.
  ❏ Calcined petroleum coke is a suitable conductive material for use as the fracture heating element.

• Modeling including the following.
  ❏ A Piceance Basin geomechanical model that shows most of the Green River oil shale is in a stress state favoring vertical, rather than horizontal, fractures.
  ❏ Heat conduction models that show several fracture designs can deliver heat effectively.
  ❏ A phase behavior model that shows volume expansion is a large potential drive mechanism. In situ oil shale can expand by 70% upon kerogen conversion.

• Resource description work indicating that Piceance Basin oil shales are sufficiently thick and rich for commercial development by the Electrofrac method.

1. INTRODUCTION

Electrofrac is an energy-efficient method for converting oil shale to producible oil and gas. As shown in Figure 1, the method heats oil shale in situ by hydraulically fracturing the oil shale and filling the fracture with an electrically conductive material, forming a heating element. The shale oil and gas are produced by conventional methods.

The use of fractures in Electrofrac is consistent with early screening research at ExxonMobil, aimed broadly at producing oil and gas from organic-rich rocks. This research explored over 30 technologies that potentially could be applied to this general problem. Basically, the research concluded:

• that in situ methods are preferred,
• that heat conduction is the best way to “reach into” organic-rich rock and convert it to oil and gas, and

• that linear conduction from a planar heat source is more effective than radial conduction from a wellbore.

The effectiveness of planar heat sources leads to the conclusion that their use will require far fewer heating wells to develop an oil shale resource.

Electrofrac is depicted in Figure 1 in what is expected to be a preferred geometry, using longitudinal vertical fractures created from horizontal wells, and conducting electricity from the heel to the toe of each heating well. This is not the only workable geometry, and one can envision many variations within the scope of Electrofrac. The process is applicable with either vertical or horizontal fractures.

The Electrofrac conductant must have an electrical resistivity high enough for resistive heating, yet low enough to conduct sufficient electric current. This means it must be significantly less conductive than most metals, and significantly more conductive than most insulators.
The remainder of this paper provides a review of ExxonMobil’s research on Electrofrac, which has been focused on critical technical issues. These issues include:

- Identification of a suitable Electrofrac conductant,
- Ascertaining whether electrical continuity through a fracture can be maintained when the rock is heated,
- Assessing whether oil and gas will be expelled from oil shale heated under in situ stress, and
- Designing a completion strategy for creating fractures that can deliver heat effectively.

Research addressing these issues has consisted of core-plug-scale lab experiments and numerical models. Results have been encouraging and specifically have included the following.

- Calcined petroleum coke has been identified as a candidate Electrofrac conductant.
- Experiments with simulated Electrofrac fractures have verified that, at least at core-plug scale, electrical continuity can be maintained even as kerogen is being converted to oil and gas.
- Hydrocarbon expulsion from oil shale under in situ stress has been verified by experiments conducted in a miniature load frame, designed to fit in a pressure-sealed heating vessel.
- An equation-of-state phase behavior model for the fluids generated from kerogen suggests that volume expansion upon conversion is a large potential drive mechanism for expulsion.
- Geomechanical modeling indicates most of the Piceance Basin Green River oil shale is in a stress state favoring vertical, rather than horizontal, fractures. Completion strategy work has therefore focused on vertical fracture scenarios.
- Effective heating has been verified with heat conduction models.

The remainder of this paper provides additional detail regarding these research results and is organized around the critical technical issues addressed.

2. CONDUCTANT IDENTIFICATION

As reported above, calcined petroleum coke has been identified as a candidate Electrofrac conductant. This is coke that has been heated to high temperature (1200-1400ºC), usually in a rotary kiln [1]. Calcined petroleum coke is relatively pure carbon, with higher calcining temperatures increasing its purity. It is a granular material with physical characteristics that make it amenable to being pumped into a fracture. Figure 2 shows photographs of calcined petroleum coke and a 20/40 mesh fracture proppant.
The electrical resistivity of calcined petroleum coke is in the desired range for an Electrofrac conductant and is relatively temperature-insensitive. The temperature insensitivity is illustrated by the data presented in Figure 3. These measurements were made on commercially available calcined coke. Two experiments are represented in Figure 3, each showing the measured resistivity as the sample is first heated and subsequently cooled. The data have been normalized by dividing by the resistivity at 25°C.

![Figure 3. Resistivity measurements made on commercially available calcined coke.](image)

In addition, the resistivity of calcined coke should be controllable to some extent by specifying the calcining temperature. This is illustrated by the data of Hardin et al. [2], reproduced in Figure 4.

![Figure 4. Calcining temperature controls coke resistivity. After Hardin et al. [2]](image)

3. ELECTRICAL CONTINUITY

A number of experiments were conducted to verify that electrical continuity can be maintained as kerogen adjacent to the fracture converts to oil and gas. Simulated fractures were created in core-plug samples by cutting the sample in half, milling a tray in one half to accept the conductant, and assembling an oil-shale conductant oil-shale sandwich. Conductants used were calcined petroleum coke and cast steel shot. The steel shot was used as a proxy prior to the identification of calcined coke. During assembly, stress was applied to the sandwiches using hose clamps to achieve electrical continuity. The samples were then heated to oil shale conversion temperatures. Construction of samples with simulated fractures for these electrical continuity experiments is illustrated in Figure 5.

![Figure 5. Construction of oil shale-conductant sandwiches for electrical continuity experiments.](image)

Concern about maintaining electrical continuity stems from the idea that heated oil shale will soften, allowing a granular conductant to lose contact between individual particles. If the conductant particles embed too deeply in the walls of the fracture, continuity could be lost in this manner.

The results of one electrical continuity experiment are illustrated in Figure 6. In this particular experiment, cast steel shot was used as the conductant. The entire sample was heated externally in a pressure-sealed heating vessel to 360°C for 24 hours, achieving 90% conversion of the oil shale. After the sample was cooled and
removed from the heating vessel, its electrical continuity was intact. A saw cut was made across the diameter of the sandwich, and photographs of the simulated fracture were taken. The rock indentations in the fracture face, visible in Figure 6, indicate that a minor degree of embedment did occur, but this did not disrupt the circuit.

Figure 6. Results of an externally heated electrical continuity experiment. Indentations in fracture face indicate the extent to which embedment occurred.

Figure 7 illustrates the results of a second electrical continuity experiment. This experiment was heated internally by supplying electric current to the simulated fracture.

Because the thermal conductivity of oil shale is relatively low, in a short-term, internally heated experiment it is possible to maintain a substantial temperature difference between the simulated fracture and the periphery of the sample. The sandwich in this experiment was again constructed with cast steel shot as the conductant. The circuit was heated with 20 amps of current for 5 hours. The power dissipated was around 60 watts, and at no time in the experiment was any disruption of the circuit encountered.

A thermocouple embedded in the sample reached a temperature of 268°C, from which it was estimated that the simulated fracture was at 350-400°C. Thermal expansion caused several fractures in the sample that allowed hydrocarbons to escape from the crescent of converted rock adjacent to the simulated fracture. The photo in the upper right portion of Figure 7 shows the simulated Electrofrac fracture and a rock surface that became exposed due to one of these thermally induced fractures.

The photomicrograph shows a section of the rock perpendicular to the exposed rock face shown in the photo. The steel shot in the simulated fracture, the spent oil shale, and a thermal crack cutting through the partially converted and unaltered oil
shale are all clearly visible. The bluish color is due to the fluorescent light source.

4. EXPULSION UNDER IN SITU STRESS
Another critical technical issue for the success of Electrofrac is the expulsion of hydrocarbons from oil shale heated under in situ stress. While it is well established that oil shale heated under no external stress will expel oil and gas [3], we were concerned that under significant in situ stress, hydrocarbons might not escape from the rock. To address this issue, a suite of experiments were performed in which oil shale samples were heated under simulated in situ stress.

To accomplish this, a spring-loaded frame was constructed which could apply stress to a 1-inch diameter sample. The entire device was placed in a pressure-sealed heating vessel and heated to conversion temperature. In this suite of experiments samples were heated to 400°C for 24 hours, achieving 95% conversion. Using different sets of springs the samples were loaded with up to 1000 psi. Samples were encased in Berea sandstone cylinders and jacketed and clamped to limit lateral strain. This uniaxial loading is similar to what the oil shale would experience in situ. Special alloy springs insured that the spring load did not diminish as the springs were heated along with the sample. As might be expected, oil shale samples initially expanded volumetrically, but by the end of the experiment they were smaller than their original size. The initial expansion was recorded by a piece of gold foil wrapped on one of the load frame support posts.

We concluded from these experiments that hydrocarbons will escape from heated oil shale even under in situ stress. Experiments under stress recovered 21 to 34 gal/ton from samples with a Fischer assay of 42 gal/ton.

To better understand these expulsion experiments, an equation-of-state phase behavior model was constructed for the hydrocarbon fluids generated from kerogen. Results of the model are illustrated in Figure 9 and Figure 10. The hydrocarbon composition used to construct the model was derived from Micro-Sealed Spherical Vessel...
pyrolysis experiments [4]. While these experiments and the resulting composition will not be discussed here in detail, this technique is generally used to study pyrolysis of conventional oil and gas source rocks.

At Electrofrac conditions the system would occupy 26.1 cubic feet. This 70% volume expansion provides a large drive mechanism for expelling hydrocarbons from the rock.

5. COMPLETION STRATEGY

The schematic design of a completion strategy for effective heating includes an estimate of how many Electrofrac fractures will be required, how they will be arranged geometrically, and what their dimensions will be. An important question for such a design is the orientation of the fractures. Hydraulic fractures open normal to the least principle in situ stress. So, to predict the orientation of Electrofrac fractures in the Piceance Basin, a basin-wide geomechanical model of in situ stress was constructed. This model is illustrated in Figure 11, and is described by Symington and Yale [5]. The model includes the effects of topography, tectonics, and recent erosion. It is calibrated to a variety of data including:

- Fracture stimulations that constrain the minimum principle stress,
- Borehole breakout and ellipticity observations that constrain the horizontal stress difference, and
- 1960’s-vintage fracture tests that establish the depth of the horizontal-to-vertical orientation transition at one location.

From the model, the elevation of the transition between shallow horizontal fracturing and deeper vertical fracturing was extracted. From this elevation it was concluded that most of the Piceance Green River oil shale is in a stress state favoring vertical fractures. Completion strategy work has therefore focused on vertical rather than horizontal fractures.

The resulting design is depicted in Figure 1, which will now be discussed in more detail. Heating wells in this scenario are drilled horizontally, perpendicular to the least principle in situ stress. Vertical longitudinal fractures are created from the horizontal wells and filled with Electrofrac conductant. Electrical conduction is from “heel” to “toe” in each of the heating wells. Connector wells are drilled through the fracture near the toe of each well, and the horizontal sections of the

![Phase Diagram](image)

**Figure 9.** Phase diagram derived from equation-of-state model for kerogen products.

A phase diagram derived from the model is shown in Figure 9. From the diagram we can see that fluids created from kerogen at Electrofrac conditions will be about 75% vaporized on a molar basis. Effectively, we will be boiling the oil out of the rock as it is created. This certainly helps explain our expulsion experiment results.

![Volume Changes](image)

**Figure 10.** Results of phase behavior modeling of kerogen products.

This can be viewed another way as shown in Figure 10. Before conversion, a ton of Green River oil shale would occupy 15.3 cubic feet. After conversion, the kerogen has become hydrocarbon liquid, hydrocarbon vapor, and coke.
wells are constructed of non-electrically conducting material. For reasonably spaced heating fractures, the induced stresses should not alter the least principle stress direction. This is important because it enables development using a series of fractures with known consistent orientation. Finally, multiple layers of heating wells may be stacked to increase heating efficiency.

![Geomechanical Model Calibration](image)

**Figure 11.** Piceance Basin geomechanical model for the prediction of in situ stress and the orientation of Electrofrac fractures.

The stacking of multiple layers of heating wells is further illustrated by thermal conduction models used to optimize the Electrofrac heating efficiency. Figure 12 shows a schematic diagram with two layers of stacked heating wells.

![Schematic Electrofrac configuration](image)

**Figure 12.** Schematic Electrofrac configuration with two layers of stacked heating wells.

Results of heat conduction models, based on the schematic in Figure 12, are shown in Figure 13. The temperature plots in Figure 13 show the thermal history for a case selected as “typical”. The view direction for these images is indicated on Figure 12. This case includes 5 years of heating with a total heat input sufficient to convert a 325-foot section of oil shale. The fracture spacing is 120 feet, and two staggered layers of Electrofrac fractures are used. The fractures are 150 feet high; 75 feet up and 75 feet down from the heating wellbore. The resultant heating efficiency is 74%, meaning that the injected heat, sufficient to convert a 325-foot section, actually converts only 240 feet. The remaining heat is lost to over- and underlying rocks heated to below-conversion temperatures.
Figure 13. Results of thermal conduction models for a "typical" Electrofrac case, using two layers of stacked heating wells.

It is interesting that the details of the heating pattern are quickly forgotten after the 5-year heating period ends. The heating efficiency is therefore mostly governed by more global parameters such as the heat input, heating duration and thickness heated. Details of the heat input distribution have more impact on the number of heaters required than on the efficiency. In this “typical” case we anticipate that the heated area will require only one heating well every 1.5 acres. This is a vivid illustration of the desirability of planar rather than radial heat sources, which we estimate might require nearly 20 times as many wells.

6. SUMMARY

In summary, ExxonMobil’s Electrofrac process is an energy-efficient method for converting oil shale to producible oil and gas. Electrofrac research has focused on critical technical issues and includes both lab experiments and numerical models. The experiments demonstrate:

- That calcined coke is a suitable Electrofrac conductant,
- That electrical continuity is unaffected by kerogen conversion, and
- That hydrocarbons will be expelled from heated oil shale even under in situ stress.

The modeling results include:

- A phase behavior model that shows volume expansion is a large potential drive mechanism for expulsion,
- A geomechanical model that shows the dominant stress state of the Piceance Basin Green River oil shale favors vertical fractures, and
- Heat conduction models that show several fracture designs can deliver heat effectively. A “typical” case requires one Electrofrac heating well every 1.5 acres, improving process economics and reducing land disturbance as compared with radial wellbore heaters.
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REFERENCES


