Heat Conduction Modeling Tools for Screening *In Situ* Oil Shale Conversion Processes

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**ABSTRACT:** Simulation methods for *in situ* oil shale conversion processes are immature compared to the tools available for conventional oil and gas reservoir management. And, while thermal reservoir simulators for heavy oil processes have existed for a number of years, no thermal simulation program is currently available that includes all the coupled physical processes necessary to model *in situ* oil shale conversion.

In the absence of a comprehensive *in situ* oil shale simulator, simple screening tools provide an effective approximate method for defining optimal process parameters such as heater geometry, heating program duration, and total heat input. Also, given the relatively immature development state of *in situ* conversion processes generally, such screening tools can help effectively focus further research on the most important process aspects.

This paper discusses screening tools used by the authors to design and evaluate *in situ* oil shale conversion processes. These computer-based tools apply superposition of conductive heat sources to create a 3D time-temperature model for the oil shale zone being targeted. Kinetic models, similar to those used in basin modeling for conventional oil and gas source rock analysis, are then applied to estimate the kerogen conversion. To consider large numbers of cases, the kinetic models can be used to create a translation table between maximum temperature achieved and fraction of kerogen converted.

The use of these screening tools will be illustrated with examples taken from the Green River oil shale in Colorado and the Rundle oil shale deposit in Queensland, Australia.

1. **INTRODUCTION**

Simulation methods for *in situ* oil shale conversion processes are immature compared to the tools available for conventional oil and gas reservoir management. And, while thermal reservoir simulators for heavy oil processes have existed for many years, no simulation program is currently available that includes all the coupled physical processes necessary to completely model *in situ* oil shale conversion.

This can be illustrated using ExxonMobil’s *Electrofrac* process as an example. As shown in Figure 1, *Electrofrac* 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 then produced conventionally. Setting aside for a moment the physics of electricity flow in the fracture, a complete simulation capability for the physical problem would require, at a minimum:

- Calculation of thermal conduction and convection,
- A coupled thermal-geomechanical model, for predicting permeability created by thermal stresses,
- A kinetic model for kerogen decomposition into oil and gas,
- An additional kinetic model for secondary cracking of the generated hydrocarbon liquids,
- Multi-phase fluid flow calculations for oil, gas, and water, and
- Modeling of multi-component hydrocarbon phase behavior.

This is a daunting task, and the authors are not aware of a simulation program with all the required capabilities. Of course, there’s also the difficulty of describing the rock and fluid physical properties such a model would require as input if it did exist.

Fortunately, one can go a long way toward understanding and evaluating *in situ* conversion
processes using screening tools that address only the most critical aspects of the process physics. At ExxonMobil we have developed a set of computer-based screening tools that account for thermal conduction and couple the temperature results to a kinetic model of kerogen decomposition into oil and gas.

The remainder of this paper describes these screening tools. It provides examples of their application to ExxonMobil’s Electrofrac process development work and to a site specific evaluation of in situ processing applicability to ExxonMobil’s Rundle oil shale resource in Queensland, Australia.

2. SCREENING TOOL DESCRIPTION

ExxonMobil’s screening tools effectively combine linear heat conduction theory and basin modeling source rock calculations. By linear conduction theory, arbitrary arrangements of heat sources are modeled by superposing time sequences of an initial value problem for an “instantly heated” rectangular solid embedded in an infinite medium. The basic initial value problem used in this superposition approach is illustrated in Figure 2, along with its mathematical solution as described by Eckert and Drake [1]. The mathematical solution is represented in terms of error functions, and computers can easily handle the superposition of many heaters. Complex heating programs are treated as a series of heaters turned on and off, and basic anisotropy can be included using direction-dependent thermal diffusivities, represented by “α” in the equations in Figure 2. Another advantage of the approach is that calculations are performed only at sites of interest, rather than over an entire numerical grid.

\[
T = T_0 + \Delta T \int_0^t f(x,t) g(y,t) h(z,t) dt
\]

Figure 2. Basic initial value problem for temperature calculation by linear superposition.

The temperature histories calculated in this manner are input to a kinetic model of kerogen decomposition. Basin modeling tools, used in conventional oil and gas exploration, are a ready-made library of these kinetic models. The models can either use end-member source rock types (usually based on Van Krevelen types [2]) or measured kinetics. They usually implement a simple chemistry model such as the one below.

Kerogen \Rightarrow Oil + Gas + Coke
Oil \Rightarrow Gas + Coke

In this model, kerogen decomposes to oil, gas, and coke. The oil then further decomposes to gas and coke. The kerogen decomposition obeys first order reaction kinetics, modeled using a spectrum of activation energies as illustrated in Figure 3.
Example calculations from a model of this type are shown in Figure 4 for constant heating rates spanning a geologic rate of 3 °C/Ma to in situ conversion rates of 50-100 °C/year.

At in situ process heating rates, the conversion temperatures are relatively insensitive to the heating rate. This leads to a further approximation often used to increase the number of screening cases that can be considered: that is relating the fraction of kerogen converted to the maximum temperature achieved by the rock, using a nominal heating rate characteristic of the process as a whole.

Combining linear heat conduction theory and kinetic modeling of kerogen decomposition leads to a general procedure for screening calculations, which is illustrated in Figure 5. The procedure starts in the upper left corner of the figure and continues around clockwise.

First, the heating scenario being evaluated is described as a set of rectangular volumetric heaters, which are turned on and off to mimic the field operation. The description must include all the heaters that impact the zone of interest. Often this results in several thousands of “mathematical heaters.”

**Figure 4.** Example calculated yields (in grams/gram of Original Total Organic Carbon) from a kerogen chemical decomposition model.

**Figure 5.** Generalized procedure for in situ oil shale screening calculations.
This list of heaters is processed by a computer program that calculates temperature and outputs it to a display program. The display program used by the authors has source rock models from ExxonMobil’s proprietary Stellar™ basin modeling software built into it, but other, more generally available, basin modeling software might just as easily fill this role. The display program assembles thermal histories and convolves them with the source rock model to calculate the oil and gas generation history. As already mentioned, a “full-math” source rock model may be used, but frequently the fraction of kerogen converted is simply estimated from the maximum temperature achieved at a given point.

Finally, the display program can sum up the oil and gas generated, for comparison to the total heat energy input.

3. PROCESS DEVELOPMENT APPLICATION

The above described screening procedure has been applied as part of ExxonMobil’s Electrofrac process development work. The rock physical properties used for these calculations are summarized in Table 1 and are based on Green River oil shale. Important parameters for heat conduction are the heat capacity, density, and thermal conductivity, which result in a thermal diffusivity of 0.607 ft²/day. Our calculations assumed a relationship between fractional kerogen conversion and maximum temperature achieved, with a conversion temperature window of 500-615°F. Finally, we assumed a nominal oil shale richness of 30 gal/ton by Fischer assay.

Figure 6 illustrates how Electrofracs are parsed into “mathematical heaters” for screening calculations. The upper left portion of the figure shows a process schematic with numerous side-by-side Electrofracs. The expected fracture voltage distribution is shown in the lower left. The linear voltage variation indicates that a two-dimensional treatment of the heat transfer is adequate. The geometry is therefore fully characterized by the fracture height and spacing as shown in the upper right. The linear voltage variation also indicates that heat generation in the Electrofrac will mimic the fracture thickness. From hydraulic fracturing theory, the fracture thickness should vary as the square-root of the distance from the tip, as shown in the lower right. To account for this dependence of heating on position, each Electrofrac is parsed into a series of fracture slivers, each running the length of the fracture. For instance, a 150 foot high fracture can be divided into 150 one-foot slivers. Discretizing the fractures in this manner can easily generate several thousand mathematical heaters.

An example screening calculation result is shown in Figure 7. This example uses 150-foot fractures. It models a 5-year heating program with a total heat input sufficient to convert a 200-foot section of oil shale. This is an amount of heat sufficient to take a 200-foot section from its assumed ambient temperature of 75°F to its complete conversion temperature of 615°F. Normalizing the heat input in this manner is a convenience used throughout the remainder of this paper. Finally, the fracture spacing is 100 feet.

The upper images show the temperature history and the lower images show the fractional kerogen conversion. The view direction is indicated on the schematic in the upper right corner. When the fractional conversion is summed-up by the display program, the result is that, effectively, 118 feet of oil shale are actually converted by the process. The ratio of these 118 feet to the 200 feet that could have been converted is defined as a heating efficiency and is considered a useful metric of process effectiveness. For this case the heating efficiency is 59%. The remaining heat is lost to over- and underlying rocks heated to below-conversion temperatures.

<table>
<thead>
<tr>
<th>Electrofrac Screening Analysis Parameters (Based on Green River Oil Shale)</th>
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<tbody>
<tr>
<td><strong>Heat Capacity</strong> (BTU/lb-°F)</td>
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<tr>
<td><strong>Thermal Conductivity</strong> (BTU/day-ft-°F)</td>
</tr>
<tr>
<td><strong>Density</strong> (lb/ft³)</td>
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<tr>
<td><strong>Thermal Diffusivity</strong> (ft²/day)</td>
</tr>
<tr>
<td><strong>Temperature window for conversion at</strong> 180 °F/year (°F)</td>
</tr>
<tr>
<td><strong>Oil Shale Richness</strong> (gallons/ton)</td>
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</table>

Table 1. Rock physical properties for Electrofrac screening calculations.
• **Case Specifics:** 150-foot fracture height, 5-year heating program sufficient to convert 200 feet of oil shale, 100-foot fracture spacing.

• **Heating Efficiency:** Ratio of oil shale actually converted to the oil shale that could be converted by the heat input (59% for this case)

> Figure 6. Electrofracs are parsed into "mathematical heaters" for use in screening calculations.

> Figure 7. Example screening calculation temperature and kerogen conversion history.
Interestingly, details of the heating pattern are quickly forgotten after the 5-year heating period ends. The heating efficiency is therefore mostly governed by global parameters such as heat input and duration and the vertical thickness heated. Details of the heat input distribution have more impact on the spacing, or number of heaters required, than the efficiency.

Screening tools can consider many combinations of the global parameters that influence heating efficiency. Figure 8 provides a vivid illustration of this advantage. Each individual graph in the figure shows heating efficiencies calculated for a specific heating program duration and fracture height. Six fracture spacings are considered, and the heat input is varied to identify an optimum value. The optimum heat input is typically sufficient to convert an oil shale interval slightly larger than the 150-foot fracture height.

Collectively, the graphs on Figure 8 show the results of varying the fracture height and heating program duration. They also illustrate that screening tools can readily make many such calculations. The data on these plots represent 792 separate screening runs.

The calculations show a trend toward higher heating efficiency at larger fracture heights. This trend highlights the importance of how high a fracture can be reliably made. We consider 150 feet to be a reasonably achievable target height for Electrofrac fractures. Therefore, to obtain a higher heating efficiency, we think multiple layers of Electrofracs will be required. This is illustrated in Figure 9.

![Tip-to-Tip Fracture Height](image)

<table>
<thead>
<tr>
<th>100 Feet</th>
<th>150 Feet</th>
<th>200 Feet</th>
<th>250 Feet</th>
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<td><strong>Heating Efficiency</strong></td>
<td><strong>Heating Efficiency</strong></td>
<td><strong>Heating Efficiency</strong></td>
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</table>

Figure 8. Screening tools can consider numerous cases, varying numerous process parameters.

Figure 9 shows a screening case that was labeled as “typical” when ExxonMobil’s Electrofrac research was first presented at the 26th Oil Shale Symposium [3]. The case includes five 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 the applied heat, sufficient to convert a 325-foot section, actually only converts 240 feet. Again, the remaining heat is lost to over- and underlying rocks heated to below-conversion temperatures.

Based on this calculation, we anticipate this "typical" case would require only one heating well every 1.5 acres, minimizing the surface disturbance required for an Electrofrac project.

**Case Specifics:** 150-foot fracture height (2 layers), 5-year heating program sufficient to convert 325 feet of oil shale, 120-foot fracture spacing.

**Heating Efficiency:** 74%

In summing up the fractional kerogen conversion to calculate the heating efficiency, we also produce a profile of hydrocarbon generation through time. Figure 10 shows the profile for this typical case, presented in a normalized fashion. Interestingly, the peak generation rate does not occur until about 15 months after the heating period ends, and significant generation continues until almost three years after heating. It is probably also worth noting that our screening tools calculate hydrocarbons generated; calculating hydrocarbons actually recovered would require the full-physics simulation that was discussed at the beginning of this paper.
Another particularly useful application of screening tools is to assess the impact of things that might go wrong in the implementation of an *in situ* conversion process. Figure 11 illustrates the use of screening tools to consider the potential impact of fracture placement errors.

The base case in Figure 11 is the “typical” case just reviewed in detail. The sensitivities examine progressively larger errors in fracture placement. The first sensitivity run has fractures placed alternately 15 feet high and 15 feet low. Additional sensitivities examine the impact of larger errors.

The calculations indicate that minor errors in fracture placement, on the order of 10-20 feet, have a minimal impact on heating efficiency. Even with errors as high as 50 feet, the heating efficiency should remain above 60 percent.

4. RESOURCE ASSESSMENT APPLICATION

Screening tools can also be used to assess the suitability of a particular oil shale resource for *in situ* conversion. In this section we describe the application of our screening tools to the Rundle oil shale deposit in Queensland, Australia. The Rundle deposit is an Esso-operated asset acquired in 1980. It is located in northeastern Queensland, near Curtis Island. Its location is indicated on the map of Australia in Figure 12.
The Rundle geology has been described in detail by Coshell [4], and is summarized in Figure 13. Geologically, Rundle is an extensional half-graben bounded to the southwest by a major fault which juxtaposes Palaeozoic basement against Eocene oil shale. The oil shale at Rundle is a lacustrine claystone, and the stratigraphy consists of alternately rich and lean oil shale beds. Historically, Rundle was considered a candidate for mining and surface retorting, with attention focused on the shallow Kerosene Creek member. Our screening study evaluated the in situ potential of the deeper Brick Kiln and Ramsay Crossing members. The Brick Kiln contains rich oil shale. The Ramsay Crossing includes a lean upper member and a rich lower member.

Our screening calculations focused on applying Electrofrac to either the Brick Kiln alone or the Brick Kiln to Lower Ramsay Crossing interval. Because of the relatively shallow depth, bedding-parallel fractures are considered likely, and several arrangements of sub-horizontal fractures were considered. These included “in-plane” fractures, “staggered non-overlapping” fractures, and “staggered overlapping” fractures for which the degree of overlap is 25%. These configurations are illustrated in Figure 14.
In-Plane Fractures

Vertical Spacing

Horizontal Spacing

Staggered Non-Overlapping Fractures

Staggered Overlapping Fractures

Horizontal Spacing

Figure 14. Configurations of sub-horizontal fractures considered in Rundle screening calculations.

Our screening cases varied numerous parameters, including the fracture geometry, size, and spacing, the heat input and duration, and the rock physical properties. Base case properties used to screen Rundle are shown in Table 2, along with Green River screening parameters for comparison. There are notable differences in the heat capacity, thermal conductivity and diffusivity, the conversion temperature window, and oil shale richness.

<table>
<thead>
<tr>
<th></th>
<th>Electrofrac Screening</th>
<th>Rundle Screening</th>
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<tbody>
<tr>
<td>Heat Capacity</td>
<td>Green River</td>
<td>Rundle</td>
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<tr>
<td>(BTU/lb-°F)</td>
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<td>Thermal Conductivity</td>
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<td>(BTU/day-ft-°F)</td>
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<td>Density</td>
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<tr>
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<td>137</td>
<td>135</td>
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<tr>
<td>Thermal Diffusivity</td>
<td>(ft/day)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.607</td>
<td>0.098</td>
</tr>
<tr>
<td>Temperature window for conversion at 180 °F/year (°F)</td>
<td>500 to 615</td>
<td>514 to 644</td>
</tr>
<tr>
<td>Oil Shale Richness (gallons/ton)</td>
<td>30</td>
<td>19 to 22</td>
</tr>
</tbody>
</table>

Table 2. Rock physical properties for Rundle screening calculations.

Results from a number of our Rundle screening runs are summarized in Figure 15. The graphs in the figure display heating efficiencies for three layers of 150-foot fractures in the “in-plane”, “staggered non-overlapping” and “staggered overlapping” configurations. These configurations would be suitable for a project implemented entirely within the Brick Kiln member. Of these three configurations, staggered overlapping fractures achieve the highest heating efficiency. The calculations consider variations in the heating program length, the fracture spacing, and the total heat input.

Even higher efficiencies can be attained by treating a thicker interval corresponding to the Brick Kiln through Lower Ramsay Crossing members. The graph in Figure 16 displays heating
efficiency for seven layers of staggered overlapping fractures. Because of Rundle’s low thermal conductivity, heating efficiencies in excess of 90% can be achieved. The low thermal conductivity also limits the fracture spacing to values less than those of our Green River calculations.

Although Rundle oil shale has a higher heat requirement for conversion because of its higher heat capacity and conversion temperature window, this may be partially offset by the higher heating efficiency.

From the seven-layer runs displayed in Figure 16, a “typical Rundle” case was selected. This case is indicated by the star on the heating efficiency plot.

Results for the typical Rundle case are shown in Figure 17. Specifically, the case models seven layers of 150-foot fractures in a staggered overlapping configuration with a 60-foot fracture spacing. The heating program duration is five years with a total heat input sufficient to convert a 400-foot section of Rundle oil shale. The resulting heating efficiency is 94%.

As before, the upper images show temperature and the lower images show the fraction of kerogen converted. One impact of Rundle’s lower thermal conductivity is apparent on these images. Although heating is discontinued at five years, conversion continues out to the 10-15 year range.
• **Case Specifics:** 150-foot fracture width (7 layers), 5-year heating program sufficient to convert 400 feet of oil shale, 60-foot vertical fracture spacing.

• **Heating Efficiency:** 94%

This can be seen even more clearly on the normalized hydrocarbon generation profile for this case, which is shown in Figure 18. The increased generation rate at 7-10 years corresponds to oil shale mid-way between fracture heaters finally reaching the generation window.

Our conclusion from this screening work is that Rundle may represent a viable target for **in situ** conversion processes and for Electrofrac in particular. As our technology matures, as a result of ExxonMobil’s ongoing field experiments in Colorado, we will continue to integrate our learnings into the assessment of Rundle’s suitability for **in situ** conversion.

5. SUMMARY

Screening tools based on linear heat conduction and basin modeling source rock calculations can provide useful estimates of **in situ** process effectiveness and resource suitability.

For **in situ** process development work, screening tools can:

- Estimate process conversion,
- Examine the impact of varying process parameters such as heating geometry, size, spacing, total heat input, and heating duration, and
➤ Assess process sensitivity to implementation problems such as imperfect heating geometry or performance.

For resource assessment, screening tools can:
➤ Estimate resource suitability for in situ processing, and
➤ Examine the impact of rock physical property variations.

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REFERENCES

