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

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**In Situ Oil Shale Screening Calculations Address the Most Critical Aspects of the Process Physics**

**Full Physical Problem**
- Thermal conduction and advection
- Coupled geomechanical model for predicting permeability creation
- Kinetic model of kerogen chemical decomposition
- Secondary cracking of oil to lighter hydrocarbons and coke
- Multi-phase fluid flow of oil, gas, and water
- Multi-component hydrocarbon phase behavior model

**Screening Calculations**
- Thermal Conduction
- Kinetic model of kerogen chemical decomposition
Screening Tools Utilize Linear Heat Conduction Theory and Basin Modeling of Source Rocks

Linear Heat Conduction Theory

Rectangular solid heated by $\Delta T$ degrees at time, $t = 0$

$$T = T_0 + \Delta T \cdot f(x,t) \cdot g(y,t) \cdot h(z,t)$$

where:

$$f(x,t) = \frac{1}{2} \left( \text{erf} \left( \frac{a - x}{2\sqrt{\alpha t}} \right) + \text{erf} \left( \frac{a + x}{2\sqrt{\alpha t}} \right) \right)$$

$$g(y,t) = \frac{1}{2} \left( \text{erf} \left( \frac{b - y}{2\sqrt{\alpha t}} \right) + \text{erf} \left( \frac{b + y}{2\sqrt{\alpha t}} \right) \right)$$

$$h(z,t) = \frac{1}{2} \left( \text{erf} \left( \frac{c - z}{2\sqrt{\alpha t}} \right) + \text{erf} \left( \frac{c + z}{2\sqrt{\alpha t}} \right) \right)$$

Basic Initial Value Problem (*)

- Arbitrary heat sources modeled as time sequences of a basic initial value problem.
- Complicated heating programs can be treated as a series of “heaters” turned on/off.
- Basic anisotropy can be included.
- Calculations done only at sites of interest.

Basin Modeling of Source Rocks

- Can use end member source rock types or measured kinetics.
- Simplified chemistry model.

Kerogen $\Rightarrow$ Oil + Gas + Coke

Oil $\Rightarrow$ Gas + Coke

- First order reaction kinetics.

Example Activation Energy Spectrum

$$\frac{dK}{dt} = A \sum_i f_i e^{\frac{E_i}{RT}}$$

Example Calculated Yield

Screening Calculations Follow a Generalized Procedure

• Describe heating scenario as a set of rectangular volumetric heaters.
• Include all heaters with an impact on the zone of interest.

• Sum up total oil & gas generated.
• Compare to heat energy input.

• Superpose heaters to calculate temperature history at points of interest.

• Convolve thermal histories with basin modeling source rock model to calculate oil & gas generation history.
• Use full math model or relate fractional conversion to maximum temperature reached.

\[
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\]
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### Electrofrac Screening Analysis Parameters
(Based on Green River Oil Shale)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Capacity (BTU/lb-°F)</td>
<td>0.3</td>
</tr>
<tr>
<td>Thermal Conductivity (BTU/day-ft-°F)</td>
<td>25</td>
</tr>
<tr>
<td>Density (lb/ft³)</td>
<td>137</td>
</tr>
<tr>
<td>Thermal Diffusivity (ft²/day)</td>
<td>0.607</td>
</tr>
<tr>
<td>Temperature window for conversion at 180 °F/year (°F)</td>
<td>500 to 615</td>
</tr>
<tr>
<td>Oil Shale Richness (gallons/ton)</td>
<td>30</td>
</tr>
</tbody>
</table>
Electrofrac Fractures are Parsed into Small Uniform Heaters for Screening Tool Application

Voltage in a “Long” Fracture is Nearly Linear

Permits a 2-D Treatment of Heat Transfer

(dimensions in feet)
Screening Tools Permit Evaluation of Overall Process Effectiveness

- **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)
Screening Tools Can Consider Numerous Cases, Varying Multiple Process Parameters

Five-year Heating Program
150-foot Fracture Height

Heating Efficiency

Spacing (feet)
- 40
- 60
- 80
- 100
- 120
- 140

Heat Input, feet of oil shale
Screening Tools Can Consider Numerous Cases, Varying Multiple Process Parameters

Tip-to-Tip Fracture Height

- 100 Feet
- 150 Feet
- 200 Feet
- 250 Feet

Heating Program Length
- 3 years
- 5 years
- 7 years

Heating Efficieny

Heat Input, feet of oil shale

Spacing (feet)

40 60 80 100 120 140

Heating Efficiency

40 60 80 100 120 140

Tip-to-Tip Fracture Height

100 Feet 150 Feet 200 Feet 250 Feet

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Screening Tools Indicate Multiple Layers of Electrofracs Improve Heating Efficiency

- **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%

\(^(*)\) – "ExxonMobil's Electrofrac™ Process for In Situ Oil Shale Conversion", 2006, Symington, et. al.
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Screening Tools Can Assess Severity of Process Imperfections – Example: Fracture Placement

Heating Efficiency is Relatively Insensitive to Minor Errors in Fracture Placement

Temperature after Five-year Heating Program

Heating Efficiency

Vertical Offset, ft

ºF

0–100
100–200
200–300
300–400
400–500
500–600
600–700
700–800
800–900
900–1000
1000–1100
1100–1200
1200–1300
1300–1400
1400–1500
1500–1600

100 ft

Spot on

15-foot miss

30-foot miss

45-foot miss

60-foot miss

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0

0 15 30 45 60

Vertical Offset, ft
Screening Tools Can Assess Resource Suitability for In Situ Processes – Rundle Example

- Esso-operated asset, originally acquired in 1980.
- Extensional half-graben with probable recent compressional reactivation.
- Historically considered a candidate for mining and surface retorting. Attention focused on Kerosene Creek Member.
- Screening tools used to evaluate in situ potential of deeper Brick Kiln and Ramsay Crossing Members.

(*) – “Cyclic Depositional Sequences in the Rundle Oil Shale Deposit”, 1983, L. Cosshel
Rundle Screening Study Considered Multiple Electrofrac Heater Arrangements

- Study focused on application of Electrofrac to Rundle Brick Kiln and Ramsay Crossing Members.
- Shallow depth and recent compressional tectonics indicate bedding-parallel fractures are likely.
- Screening study varied numerous parameters.
  - Geometry
  - Fracture size
  - Fracture spacing
  - Heat input
  - Heating duration
  - Physical properties

### Screening Analysis Physical Parameters

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<tr>
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<th>Rundle Screening</th>
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<td>19 to 22</td>
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Overall Process Effectiveness Depends Most Strongly on Extent of Heated Interval

- Staggered, overlapping fractures are highly efficient.
- Highest efficiencies occur when heating the entire Brick Kiln to Lower Ramsay Crossing interval.
- Lower thermal conductivity limits vertical spacing.
- Rundle’s higher heat requirement (relative to Green River) may be offset by higher heating efficiency.

### Seven Layers of 150-foot Staggered Fractures
(Suitable for Brick Kiln to Lower Ramsay Crossing)

#### Heating Program
- 3 years
- 5 years
- 7 years

#### Fracture Spacing
- 45 ft
- 60 ft
- 75 ft
- 90 ft

### Three Layers of 150-foot Fractures
(Suitable for Brick Kiln Member)
Heating the Brick Kiln / Ramsay Crossing Interval Provides a High Heating Efficiency

- **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%
**Heating the Brick Kiln / Ramsay Crossing Interval Provides a High Heating Efficiency**

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**Temperature**

**Normalized Hydrocarbon Generation**

- **Total Generation**
- **Generation Rate**

**Fraction of Kerogen Converted**

**Time, years**

**View Direction**

**End of Heating**

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**Legend**

- 0°F
- 0.0
- 1.0
- 2.5 years
- 15 years
- 50 ft
- 0.0
- 1.0
Screening tools based on linear heat conduction and basin modeling source rock calculations provide useful estimates of process effectiveness and resource suitability.

- For *in situ* process development work, screening tools can:
  - Estimate process conversion.
  - Examine impacts of process parameters such as heating geometry, size, spacing, total heat input, and heating duration.
  - Assess process sensitivity to implementation problems such as imperfect heating geometry or performance.

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