Oil Shale: Is Now the Time?

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Garfield County Energy Advisory Board
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Outline

- What are Oil Shale and Shale Oil?
- Geology, Stratigraphy and Resources
- Production Technology in the United States
- How Fast Can it Grow?
- Responsible Oil Shale Development
- Environmental Issues for Oil Shale Production
What is oil shale?

• Organic rich mudstone formed in lake or marine environments
  – Commonly carbonate rich; many not classical clay-rich mudstones (shale)
  – Kerogen-rich, primarily algal and bacterial remains
  – Immature precursor to oil & gas

• Produces oil on short term heating to temperatures above ~300° C
Global Oil Shale Resource Estimates

1. Green River Formation
   >3,000,000 million barrels
   Tertiary, lacustrine

2. Other United States
   619,000 million barrels
   Eastern Devonian, Phosphoria, Heath
   Devonian-Permian, marine

3. China
   328,000 million barrels
   Primarily Tertiary, lacustrine

4. Russia
   270,944 million barrels
   Ordovician-Jurassic, marine

5. Israel
   250,000 million barrels
   Cretaceous, marine

6. Jordan
   102,000 million barrels
   Cretaceous, marine

7. Brazil
   80,000 million barrels
   Permian, lacustrine or marine
   Tertiary, lacustrine

8. Morocco
   57,800 million barrels
   Cretaceous, marine

9. Australia
   24,000 million barrels
   Cretaceous, marine
   Tertiary, lacustrine

10. Estonia
    16,286 million barrels
    Ordovician, marine

11. Canada
    15,241 million barrels
    Ordovician-Devonian, marine
    Carboniferous, lacustrine
    Mesozoic, marine

12. Thailand
    6,401 million barrels
    Tertiary, lacustrine

13. Sweden
    6,114 million barrels
    Cambrian-Ordovician, marine

14. Egypt
    5,700 million barrels
    Cretaceous, marine

15. Ukraine
    4,193 million barrels

16. Kazakhstan
    2,837 million barrels

Updates from 26th through 30th Oil Shale Symposia, Colorado School of Mines
Shale – the most abundant sedimentary rock
Shale composition covers a lot of ground
Oil shale, oil–bearing shale, and gas shale

Source - USGS, Petroleum Systems and Geologic Assessment of Oil and Gas in the Uinta-Piceance Province, Utah and Colorado
Bakken – Green River Comparison

- Green River
- Bakken

TOC (wt %)

0 10 20 30 40

0 500 1000 1500 2000 2500 3000 3500

GR Density / Neutron

Shale
Arg. Dolomite
Sandstone/Limestone
Limestone, Slitst (var arg.
Shale
GEOLOGY, STRATIGRAPHY AND RESOURCES
New USGS assessment of Piceance Basin resources (from Johnson et al., 2010)

<table>
<thead>
<tr>
<th>Zone #</th>
<th>Oil in place (BBO)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>R zone</td>
</tr>
<tr>
<td>8</td>
<td>189.7</td>
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<tr>
<td>7</td>
<td>191.7</td>
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</tr>
<tr>
<td>6</td>
<td>185.4</td>
<td></td>
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<tr>
<td>5</td>
<td>198.2</td>
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<td>4</td>
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<tr>
<td>3</td>
<td>68.1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>66.8</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>195.4</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>83.4</td>
<td></td>
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<tr>
<td>Total</td>
<td>1305.8</td>
<td></td>
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</tbody>
</table>
Lake Uinta, 50 million years ago
Humid climate, high runoff (rich oil shale)
Alternating with:
Arid climate, low runoff (lean oil shale)

- Littoral, sublittoral siliciclastic rocks
- Evaporite deposits (halite, nahcolite)
- Laminated oil shale
Lake Stages and Climate

from Zachos et al., 2001

High lake level (S4, 5, & 6)
Rapidly fluctuating lake (S3)
High sand input (S2)
Freshwater lake (S1)

Temperature (°C)*
Deep lake deposits

- Halite crystals
- Nahcolite crystals
- Oil shale

Halite bottom growth
Areal Richness of Mahogany Zone

• One zone contains up to 450,000 barrels/acre (BPA)

• Overall richness may be more than 1,000,000 BPA
Oil Shale Resources of Green River Formation

- Piceance Basin: 1,335 square miles (3,458 km²).
  - In place resource: 1.52 trillion barrels
- Uinta Basin: 3,834 square miles (9,930 km²).
  - In-place resource: 1.32 trillion barrels
- Greater Green River Basin: 5,500 square miles (km²).
  - In-place resource less than Piceance and more than Uinta Basin.
  - The Piceance Basin has the smallest area and largest resource.
Sodium Carbonate Minerals in Colorado, Utah, and Wyoming

• The Piceance Basin contains the second largest deposit of sodium carbonate as Nahcolite (NaHCO₃) in the Parachute Creek Member of the GRF.

• The world’s largest deposit of sodium carbonate is in the Green River Basin of SW Wyoming as trona (Na₃(CO₃)(HCO₃)·2H₂O) in the Wilkins Peak Member of the GRF.

• Uinta Basin contains minor deposit of bedded sodium carbonate minerals in the GRF near Duchesne, Utah.
OIL SHALE PRODUCTION TECHNOLOGY
ATP Retort at Fushun China
Enefit 280 Under Construction

July 7, 2011
Shell In–Situ Conversion Process (ICP)

- Electric resistance heaters gradually heat shale in subsurface
- Applicable to oil shale and heavy oil/bitumen
- Accelerates natural maturation of kerogen by gradual heating in oil shale
- High recoveries & light hydrocarbon products yielding high quality transportation fuels
Better Feedstock For Upgrading

Shell In Situ Pyrolysis

45 API Gravity

19 API Gravity

Surface Retort Pyrolysis

350°C In Situ

SHALE OIL EXAMPLE

Naphtha - 30%
Diesel - 30%
Jet - 30%
Resid - 10%

Tar Like Solid

NAPHTHA JET DIESEL RESID

800°C Surface Retort

Weight %

Carbon Number

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT
Freeze Wall for Ground Water Protection

- Closely space boreholes circulating liquid ammonia freeze mobile ground water
- Buffer zone isolates heated block from freeze wall
- Production wells remove mobile water from block before heating
- Heaters pyrolyze rock in heated zone to recover hydrocarbons
- Additional wells circulate water through heated block to “steam clean” any trapped hydrocarbons
- Freeze wall allowed to thaw when cleaning is complete
ExxonMobil Electrofrac™ Process

• Create electrically conductive fractures (vertical or horizontal)

• Planar heat source more effective than radial conduction from wellbore

• Typical simulation
  – 150 foot fracture height
  – 5-year heating converts 325 feet of oil shale
  – 120-ft fracture spacing
  – 74% heating efficiency
AMSO CCR™ Process

- AMSO’s patent-pending CCR™ process uses convection to accelerate heat transfer throughout the retort
- Faster heat transfer in the process enables fewer wells, hence less surface impact, to extract the shale oil

* Conduction, Convection and Reflux
AMSO 2011 Pilot Test and Features of the Process

- Minimal surface footprint
- Protection of aquifers
- Low water usage
- High energy efficiency
- Low gas emissions
- High-value jobs
Chevron Approach – Rubblization & Injection

- Rubblization is breaking a zone of reservoir into discrete chunks of rock. In other words, generating fractures in the x, y, and z planes.

- Adjacent aquifers and fractures can limit the amount of surface area generated by conventional fracturing. Rubblization can provide the high surface area needed for our conversion chemicals within a compact zone.
Potential Rubblization Methods

• Thermal (Cryogenic?)
  – Rock shrinks when cooled. Extreme cooling will cause it to go into tension (vs. its normal state of being in compression)
  – The rock is weak in tension
  – The coefficient of thermal expansion varies with layers, resulting in varying amounts of shrinkage, and shear stresses which aid rubblization
  – A large amount of cooling is needed
  – Some control over where the cooling is done

• Explosive
  – Timed explosives to generate “constructive interference”
  – Drilling intensive
  – Control over height and direction. Ability to “generate shapes”
EcoShale™ In-Capsule Process

- Combines the benefits and avoids the shortcomings of both *in-situ* and surface technologies
  - Oil shale is mined and placed in an excavation that has been lined with an impermeable clay liner
  - Expendable closed wall heating pipes are placed horizontally throughout the capsule
  - A liquid drain system is included in the bottom of the capsule; perforated pipes at the top of the capsule collect hydrocarbon vapour
  - Clay liner completes the containment structure on top, with overburden subsequently replaced to start immediate reclamation
  - Natural gas burners produce hot exhaust gas that is circulated through the capsule
- Produces a high grade, light synthetic crude
HOW FAST CAN IT GROW?
Historic oil production

Production (BOPD)

10,000,000
1,000,000
100,000
10,000
1,000

1980 2000 2020 2040

US Oil 1862–1919
Tar Sand 1968–2007
US Oil Growth
Tar Sand Growth

9.8 %
8.7 %
Growth rate of major petroleum resources

- Canada Oil Sand
- U. S. Shale Gas
- Bakken
- Eagle Ford Gas (BOE)
- Eagle Ford Oil

Barrels per Day

Canada Oil Sand: 10000000
U. S. Shale Gas: 1000000
Bakken: 100000
Eagle Ford Gas (BOE): 9%
Eagle Ford Oil: 15%

Projected Global Oil Shale Production

Mined shale, million tonnes

Year

- Jordan
- United States
- China
- Sweden
- Germany
- Brazil
- Russia
- Scotland
- Estonia

1880 1900 1920 1940 1960 1980 2000 2020
RESPONSIBLE OIL SHALE DEVELOPMENT
Alternative B – Oil Shale (2008)

Colorado – 359,798 acres
Utah – 630,971 acres
Wyoming – 1,000,453 acres
Colorado RD&D Leases

2010 2nd Round Nominations and 2007 Leases for Oil Shale Research, Development and Demonstration 160 Acres and Preference Acreage

2010 RDD 160 Acre Tracts
- Natural Soda - 2nd Round
- ExxonMobil - 2nd Round
2007 RDD 160 Acres Leases
- Leases

2010 PRL Acreage
- Sept 10
  - Natural Soda - 2nd Round
  - ExxonMobil - 2nd Round

2007 PRL Acreage
- OCC-89156
- OCC-89154
- OCC-89159
- OCC-89157
- OCC-89155
- Multi-Mineral Zone
- Sodium Leases

Sources: BLM, USGS, COGW, etc.

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03/02/2010
Jordanian Government Focus

- Government is aware of the importance of investments in and potential environmental impacts from oil shale development.

- Government focusing on:
  - Protecting environment from possible serious impacts & high risk hazards
  - Ensuring practical regulations applied to various oil shale processes
  - Appropriate monitoring of potential pollutants

- The environment regulation must be:
  - Adaptable to address new environmental issues
  - Balanced against companies’ need for a stable investment framework

- The royalty structure must
  - Provide adequate encouragement to interested companies,
  - Provide reasonable return to the people of Jordan
Environmental framework

- Jordanian environmental laws stem from:
  - Ministry of Environment
  - Ministry of Water and Irrigation
  - Ministry of Health
  - Jordan Institution for Standards and Metrology (JISM)

- Oil shale projects will be required to comply with
  - World Bank / IFC Guidelines
  - The Equator Principles
  - Reasonable and prudent operator standards
  - Emission Limit Values as specified for the oil shale industry
Other Governmental Authorities

- By-laws of relevance to oil shale industry impacts are also issued by other different responsible governmental authorities:
  - Ministry of Energy & Natural Resources: Energy & alternative energy sources & power production projects
  - Ministry of Agriculture: Monitoring soil pollution & protecting biodiversity
  - Natural Resources Authority: Minerals exploitation & natural resources regulations
  - Civil Defense: Hazardous materials & explosive chemicals management
  - Royal Society for The Conservation of Nature: Conservation of rare species & natural reserves
  - Ministry of Tourism and Antiquities: Archeological & cultural heritage
  - Ministry of Municipals Affairs: Land use planning, urbanization, local communities
  - Ministry of Labor: Labor and occupational health
Summary of Environmental Framework for Oil Shale Industry in Jordan

Air Emissions
Ambient, End of Stack and CO2

Water Effluent and Discharge Pollutants
(Soil, S. Water & G. Water)

Mining, SRP, PP, Upgrading, Remediation and Mitigation

Solid Waste and Remediation (Air, Water and Soil)

Baseline Pollution Levels
(Air, Water and Soil)
Concession Agreement Fiscal Terms

- **Production Bonus**
  - $10 million at 2 million barrels

- **Royalty**
  - Sliding scale form 1% – 5% based on oil price – Brent reference

- **Petroleum Tax**
  - Sliding scale from 15%-65% based on ratio of Revenue / Costs

<table>
<thead>
<tr>
<th>Oil Price – Brent $/bbl</th>
<th>Royalty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brent &lt; 60</td>
<td>1%</td>
</tr>
<tr>
<td>60 ≤ Brent ≤ 120</td>
<td>(5%-1%)/(120-60)*(Brent-60)+1%</td>
</tr>
<tr>
<td>Brent &gt; 120</td>
<td>5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Revenue /Cost</th>
<th>Tax</th>
</tr>
</thead>
<tbody>
<tr>
<td>R/C &lt; 1.25</td>
<td>15%</td>
</tr>
<tr>
<td>1.25 ≤ R/C &lt; 5</td>
<td>(65%-15%)/(5-1.25)*(R/C-1.25)+15%</td>
</tr>
<tr>
<td>5 ≤ R/C</td>
<td>65%</td>
</tr>
</tbody>
</table>
ENVIRONMENTAL ISSUES FOR OIL SHALE PRODUCTION
Environmental Issues for Oil Shale Development

- **Issues**
  - Water quantity and quality
  - Carbon footprint
  - Air quality
  - Surface and ecosystem impact
  - Social and economic impacts

- **Data needs**
  - Definition process
  - Baseline collection
  - Management
  - Dissemination

- **Model development**
- **Impact assessment & policy**
- **Technology development for mitigation**
Site Water Use Depends upon Reclamation Efficiency

![Graph showing the relationship between site water use (barrels/barrel oil) and reclamation efficiency.]
Oil shale richness controls CO$_2$ release
Additional CO$_2$ release from Nahcolite
SHALE GAS AND
SHALE–HOSTED OIL
Recognized shale gas basins widely distributed
Shale is a very impermeable rock

Permeability (mD)

0.0001 0.001 0.01 0.1 1.0 10.0

Extremely Tight Very Tight Tight Low Moderate High

Source: modified after US DOE Study, 2005
Shale reservoirs must be fractured to produce

Hydraulic Fracturing
Hydraulic fracturing, or “fracing,” involves the injection of more than a million gallons of water, sand and chemicals at high pressure down and across into horizontally drilled wells as far as 10,000 feet below the surface. The pressurized mixture causes the rock layer, in this case the Marcellus Shale, to crack. These fissures are held open by the sand particles so that natural gas from the shale can flow up the well.
Knowing where your fractures are is essential.
Knowing where your fractures are is essential

Horn River microseismic
Planar Fracture growth?

Barnett Shale microseismic
Complex fracture growth
Water issues are significant for shale gas & oil

- Water quantity and quality
- Fracturing fluid disposal/contamination
  - Surface spill or release
  - Casing failure
  - Fracturing upward to aquifer?

KCl 600 ppm
Guar gum/Hydroxyethyl cellulose 560 ppm
Ethylene glycol 430 ppm
(Na,K)2CO3 110 ppm
NaCl 100 ppm
Borate salts 70 ppm
Citric acid 40 ppm
N,n-dimethyl formamide 20 ppm
Gluteraldehyde 10 ppm

Petroleum distillate 880 ppm
Acid 1230 ppm
Isopropanol 850 ppm
Fracturing fluid additives include familiar and exotic ingredients

<table>
<thead>
<tr>
<th>Additive Type</th>
<th>Main Compound</th>
<th>Purpose</th>
<th>Common Use of Main Compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid</td>
<td>Hydrochloric acid or muriatic acid</td>
<td>Helps dissolve minerals and initiate cracks in the rock</td>
<td>Swimming pool chemical and cleaner</td>
</tr>
<tr>
<td>Antibacterial</td>
<td>Glutaraldehyde</td>
<td>Eliminates bacteria in the water that produce corrosive by-products</td>
<td>Disinfectant; sterilizer for medical and dental equipment</td>
</tr>
<tr>
<td>agents</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breaker</td>
<td>Ammonium Persulfate</td>
<td>Allows a delayed break down of the gel</td>
<td>Used in hair coloring, as a disinfectant, and in the manufacture of common household plastics</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Formamide</td>
<td>Prevents the corrosion of the well casing</td>
<td>Used in pharmaceuticals, acrylic fibers and plastics</td>
</tr>
<tr>
<td>inhibitor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crosslinker</td>
<td>Borate salts</td>
<td>Maintains fluid viscosity as temperature increases</td>
<td>Used in laundry detergents, hand soaps and cosmetics</td>
</tr>
<tr>
<td>Friction</td>
<td>Petroleum distillate</td>
<td>“Slicks” the water to minimize friction</td>
<td>Used in cosmetics including hair, make-up, nail and skin products</td>
</tr>
<tr>
<td>reducer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gel</td>
<td>Guar gum or hydroxyethyl cellulose</td>
<td>Thickens the water in order to suspend the sand</td>
<td>Thickener used in cosmetics, baked goods, ice cream, toothpaste, sauces and salad dressings</td>
</tr>
<tr>
<td>Iron control</td>
<td>Citric acid</td>
<td>Prevents precipitation of metal oxides</td>
<td>Food additive; food and beverages; lemon juice –7% citric acid</td>
</tr>
<tr>
<td>Clay stabilizer</td>
<td>Potassium chloride</td>
<td>Creates a brine carrier fluid that prohibits fluid interaction with formation clays</td>
<td>Used in low-sodium table salt substitute, medicines and IV fluids</td>
</tr>
<tr>
<td>pH adjusting</td>
<td>Sodium or potassium carbonate</td>
<td>Maintains the effectiveness of other components, such as crosslinkers</td>
<td>Used in laundry detergents, soap, water softener and dishwasher detergents</td>
</tr>
<tr>
<td>agent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proppant</td>
<td>Silica, quartz sand</td>
<td>Allows the fractures to remain open so the gas can escape</td>
<td>Drinking water filtration, play sand, concrete and brick mortar</td>
</tr>
<tr>
<td>Scale inhibitor</td>
<td>Ethylene glycol</td>
<td>Prevents scale deposits in the pipe</td>
<td>Used in household cleansers, de-icer, paints and caulk</td>
</tr>
<tr>
<td>Surfactant</td>
<td>Isopropanol</td>
<td>Used to reduce the surface tension of the fracturing fluids to improve liquid recovery from the well after the frac</td>
<td>Used in glass cleaner, multi-surface cleansers, antiperspirant, deodorants and hair color</td>
</tr>
<tr>
<td>Water</td>
<td>Water</td>
<td>Used to expand fracture and deliver proppant (sand)</td>
<td>Landscaping, manufacturing</td>
</tr>
</tbody>
</table>
Aquifers must be protected from producing zones

- Treatable Groundwater Aquifers
- Private Well
- Municipal Water Well: <1,000 ft.
- Additional steel casings and cement to protect groundwater
- Protective Steel Casing
- Approximate distance from surface: 8,000 feet
BACK-UP MATERIAL
Richness of Mahogany Zone
Lake margin deposits

Progradation of delta (Yellow Creek)

Littoral, sublittoral stromatolites
Lake Uinta, 50 million years ago

- Littoral, sublittoral carbonates
- Shore sandstones (delta)
- Laminated oil shale
- Evaporites (halite, nahcolite)
AMSO Process Features

- Minimal surface footprint
- Protection of aquifers
- Low water usage
- High energy efficiency
- Low gas emissions
- High-value jobs
Red Leaf Resources Ecoshale™ Technology

The EcoShale In-Capsule Process

- Clay Liner
- Closely Spaced Heat Pipes
- Skid Mounted Equipment
- Mined Ore/Void Volume
- Sloped Drainage
- Vapor/Prompt Oil Recovery
- In-Pit Extraction
OIL AND GAS FROM THE GREEN RIVER FORMATION
Producing Oil Fields of the Green River Formation

Source – USGS, *Petroleum Systems and Geologic Assessment of Oil and Gas in the Uinta–Piceance Province, Utah and Colorado*
## Oil Production from Green River Formation Fields (BBO)

<table>
<thead>
<tr>
<th>Fields</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>Cumulative Production</th>
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<tbody>
<tr>
<td>BLUEBELL</td>
<td>2,170,166</td>
<td>2,216,764</td>
<td>1,436,909</td>
<td>168,256,774</td>
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<tr>
<td>ALTAMONT</td>
<td>1,427,141</td>
<td>1,707,755</td>
<td>1,684,601</td>
<td>125,924,864</td>
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<tr>
<td>RED WASH</td>
<td>381,585</td>
<td>377,705</td>
<td>284,608</td>
<td>85,962,385</td>
</tr>
<tr>
<td>WONSITS VALLEY</td>
<td>345,459</td>
<td>299,099</td>
<td>206,193</td>
<td>51,280,150</td>
</tr>
<tr>
<td>MONUMENT BUTTE</td>
<td>4,234,316</td>
<td>4,636,580</td>
<td>3,749,010</td>
<td>46,251,817</td>
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<tr>
<td>OTHER GRF</td>
<td>2,437,672</td>
<td>2,003,559</td>
<td>1,703,816</td>
<td>63,928,511</td>
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<tr>
<td><strong>TOTALS</strong></td>
<td>10,996,339</td>
<td>11,241,462</td>
<td>9,065,137</td>
<td>541,604,501</td>
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<tr>
<td>State Total</td>
<td>22,039,614</td>
<td>22,943,850</td>
<td>18,157,832</td>
<td>1,396,246,479</td>
</tr>
<tr>
<td>%</td>
<td>49.9%</td>
<td>49.0%</td>
<td>49.9%</td>
<td>38.8%</td>
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