Gas-Fracturing in Unconventional Reservoirs

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Prospects for Gas-Fracturing in Unconventional Reservoirs

Principal Issues in Shale Gas Production - Motivation

Energy Outlook: Security, Independence and Environment

Water-related issues

Waterless fracturing and gas displacement (ESGR)

Gas-fracturing Observations

Breakdown Pressures

PMMA/Granite/Bluestone and Structure

Key Observations

Hypotheses

Fracture Complexity

Key Observations

Hypotheses

Methods of Analysis

Mechanisms for Gas/Rock Interaction

Damage Mechanics

Summary
Implications for Energy Independence, Energy Security and for Climate Change?
North American shale plays (as of May 2011)

Source: U.S. Energy Information Administration based on data from various published studies. Canada and Mexico plays from ARI. Updated: May 9, 2011
World Shale Plays and Reserves

Legend
- Red: Assessed basins with resource estimate
- Yellow: Assessed basins without resource estimate
- White: Countries within scope of report
- Gray: Countries outside scope of report
World Shale Plays and Reserves

[http://www.eia.gov/analysis/studies/worldshalegas/]
## Consumption -versus- Reserve/Resource

### Natural Gas and Other Fossil

<table>
<thead>
<tr>
<th>Source</th>
<th>Consumption</th>
<th>Reserve/Resource</th>
<th>United States</th>
<th>World</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coalbed</td>
<td>~20/160 Tcf</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Shale</td>
<td>~32/5000 Tcf</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>~237/- Tcf</td>
<td>~6,300/- Tcf</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>~21/- Tcf</td>
<td>~289/- Tcf</td>
<td>~100 Tcf</td>
<td></td>
</tr>
<tr>
<td>Hydrates</td>
<td>-/10 Tcf</td>
<td></td>
<td>~5 Tcf</td>
<td>~5 Tcf</td>
</tr>
<tr>
<td>Oil</td>
<td>~180 Tcf</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elec. (Coal?)</td>
<td>~70 Tcf</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>~350 Tcf</td>
<td></td>
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**Global Energy Capacity** ~15 TW (10^{12} W=Trillion W)

**Annual Energy Consumption** ~ 500 EJ/y (10^{18} J/y)

1 EJ ~ 1 Quadrillion Btu ~ 1 Tcf gas

**Global Energy Consumption:** ~ 500 EJ/y

 Equivalent to: ~ 500 Quads /y

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Projected Growth and Opportunities

Natural Gas Utilization

[Science, Oct 18, 2012]

17Tcf

Trillion cubic meters

[Nature, 2011]

Secretary of Energy Advisory Board

Shale Gas Production Subcommittee Second Ninety Day Report
November 18, 2011

[Science, Oct 18, 2012]

Oxidation
2HBr + 1/2O₂ → Br₂ + H₂O

H₂O

HBr

Activation
CH₄ + Br₂ → CH₃Br + H₂

Br₂

Methylbromide coupling
CH₃Br + Products + HBr

Liquid fuels or chemicals

Wind or solar converter
ZnBr₂ → Br₂ + H₂
Issues - Rural Industrialization
Induced Seismicity

Observations of Events in Barnett Shale (TX)
- Small < -1.4
- Clustered close to fracs
- No obvious events distant from fracs
- Cease after the stimulation

[Zoback, Kitasei, Copithorne, 2010, Worldwatch Institute]
Induced Seismicity

Learning How to NOT Make Your Own Earthquakes
As fluid injections into Earth's crust trigger quakes across the United States, researchers are scrambling to learn how to avoid making more.

First off, fracking for shale gas is not touching off the earthquakes that have been shaking previously calm regions from New Mexico to Texas, Ohio, and Arkansas. But all manner of other energy-related fluid injection— including the usual removal of natural gas via hydraulic fracturing (fracking)—can lead to induced seismicity.

Earthquakes of magnitude 3 or greater have been recorded in the vicinity of every major oil and gas producing region in the United States, including Texas, Oklahoma, and Arkansas.

That's when Miroslav Scawthorn and Scott Asbury of the Arkansas Geological Survey took note of a curious cluster of earthquakes near Greersville. The Gray-Greenhorn sandstone had only one quake of magnitude 2.5 or greater in 2007 and none in 2008, but there were

[Ellsworth, Science, 2013]
Groundwater

[Zoback, Kitasei, Copithorne, 2010, Worldwatch Institute]
Groundwater Near-Wellbore

[Osborne, Vengosh, Warner, Jackson, 2011, PNAS]
Groundwater Near-Wellbore

Dissolved Gas Analyses
(This Study)
- Active Extraction Area - Catskill
- Active Extraction Area - Lockhaven
- Active Extraction Area - Genesee
- Nonactive Extraction Area - Catskill
- Nonactive Extraction Area - Genesee

Published Gas Analyses
(Production Wells)
- Pennsylvanian
- Upper Devonian
- Middle Devonian
- Silurian
- Ordovician
- Gas Wells-Susquehanna

[Osborne, Vengosh, Warner, Jackson, 2011, PNAS]

Methane Concentration (mg CH₄/L)

Distance to Nearest Gas Well (m)

Action Level for Hazard Mitigation
(US Department of Interior)

Methane Concentration (mg CH₄/L)

δ¹³C CH₄ (%o, VPDB)
Life-Cycle Loadings

A DAUNTING CLIMATE FOOTPRINT
Over 20 years, shale gas is likely to have a greater greenhouse effect than conventional gas or other fossil fuels.

[Howarth, Santoro, Ingraffea, 2011, Climatic Change]
Impacts of Abundant Gas Supply

Role of abundant natural gas supply... impact on reducing use of coal .......but also of decreasing the penetration of renewables

Permeability Evolution – Implications for Gas Recovery?

Coal

Constant Mean Stress

Gas Shale (Marcellus)

Various Mean Stresses

\[ k_0 = 2.86 \times 10^{-17} \text{ m}^2 \]

- He & N₂
- CO₂ as permeant

CO₂ as permeant - Analogous to CH₄
Capacity Needs – Socolow Wedges

The Stabilization Triangle:
Beat doubling or accept tripling

Values in parentheses are ppm. Note the identity (a fact about the size of the Earth’s atmosphere): 1 ppm = 2.1 GtC.

Capacity Needs – Socolow Wedges

Wedges

Historical emissions

Flat path

Currently projected path

14 GtC/y

7 GtC/y

1.9 → 7 Billion of Tons of Carbon Emitted per Year

1954 → 2004 → 2054 → 2104

Capacity Needs – Socolow Wedges

What is a “Wedge”? 

A “wedge” is a strategy to reduce carbon emissions that grows in 50 years from zero to 1.0 GtC/yr.

![Diagram showing a wedge with 1 GtC/yr at 50 years, total 25 Gigatons carbon]

Cumulatively, a wedge redirects the flow of 25 Gt(C) in its first 50 years. This is 2.5 trillion dollars at $100/t(C).

A “solution” to the Greenhouse problem should have the potential to provide at least one wedge.

Capacity Needs – Socolow Wedges

Fill the Stabilization Triangle with Seven Wedges

Zero carbon: 800 GW (~40 tcf/yr)

Low carbon: 1600 GW (~80 tcf/yr)

2 billion cars at 60 mpg instead of 30 mpg

CO₂ Capture and Storage

Zero carbon: 800 GW (~40 tcf/yr)

Forests & Soils

Fuel Switch

Energy Efficiency & Conservation

Renewable Electricity and Fuels

2004

Stabilization Triangle

7 GtC/yr

14 GtC/yr

Nuclear Fission

Zero carbon: 700 GW (~40 tcf/yr)

Zero carbon: 1600 GW (~80 tcf/yr)

Zero carbon: 800 GW (~40 tcf/yr)

Motivation

Gas Recovery (Improved production)
Energetic fracturing - reducing diffusion lengths

Incidental Benefits (Improved environmental protection)
Decrease water usage
Resource usage
Induced seismicity
Reduce surface transportation/disruption

Minimize effect on sensitive reservoir rocks
Avoid pore occlusion with fluids
Avoid swelling of clays
Avoid recovery of NORMS

Reduce life-cycle equivalent $CO_2$ costs
Key Coupled Processes Related to Gas-Fracturing in Unconventional Reservoirs

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  Water-related issues

  Waterless fracturing and gas displacement (ESGR)

Observations
  Breakdown Pressures
    PMMA/Granite/Bluestone and Structure
      Key Observations
      Hypotheses
  Fracture Complexity
    PMMA
      Key Observations
      Hypotheses
  Fracture Propagation Velocities

Methods of Analysis
  Mechanisms for Gas/Rock Interaction
  Damage Mechanics

Summary
Fluid Delivery

http://www.regalenergy.com/pup_multi-stageFrac.htm
Borehole Fracture in PMMA
(Polymethyl methacrylate aka: Lucite, Plexiglas, Perspex, Acrylic)
Stress State

\[ s_1 > s_2 > s_3 \]
Hydrofracture, view below is in the $s_3$ direction

$s_1 = s_2 = 10 \text{ MPa} \ (\approx 1500 \text{ psi})$

$P_{p \text{ fail}} = 43.3 \text{ MPa} \ (\approx 6200 \text{ psi})$

p3006; water
PMMA: N\textsubscript{2} hydrofrac
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Summary
$P_b$ is fluid/fluid-state dependent

$S_h = S_v = 5$ MPa

$CO_2$ Upper Bound - Tensile Strength ~ 70 MPa
$P_b$ for $CO_2:N_2$ are $\sim 2:1$ for PMMA/Bluestone.
Fracturing Fluid Properties

1. Ar, N₂ and He are supercritical (no interfacial tension)
2. Water, CO₂ and SF₆ are liquids (interfacial tension)

[Source: http://en.wikipedia.org/wiki/Critical_point_(thermodynamics)]
Complexity - $N^2$

Front

Side
Complexity – Ar

Front

Side
Complexity – \( CO_2 \)
Complexity - He

Front

Side
Fracture Complexity

Super-critical Fluids
- Helium, He
- Nitrogen, N₂
- Argon, Ar

Sub-critical Fluids
- Carbon Dioxide, CO₂
- Water, H₂O
- Sulfur Hexafluoride, SF₆
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Summary
Fluid Pressures Around Borehole

With and without borehole “membrane”

\[ \sigma_\theta = +S_H \frac{a^2}{r^2} (S_H = S_h) \quad \text{Perforated or Unperforated} \]

\[ \sigma_\theta^p = -P_0 \frac{a^2}{r^2} \quad \text{Unperforated membrane} \]

\[ p(3D) = -P_0 \frac{a}{r}; \quad p(2D) = -P_0 \frac{\ln(r)}{\ln(a)} \quad \text{Steady flow (3D,2D)} \]

Pressure, \( P_0 \)

No fluid invasion

\( p = -P_0 \)
Fluid Pressures Around Borehole

With and without borehole “membrane”

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\[ p = -P_0 \]  Static invasion (no flow)

Pressure, \( P_0 \)

No fluid invasion
Longitudinal Hydraulic Fracture

Fracture Breakdown Pressure for fracture along borehole (plane strain)

"Permeable:"

\[ \sigma_T = \sigma_{\theta\theta} = 3S_h - S_H - P_0 + (1 + \eta)P_w \]

\[ \eta = \frac{v}{1 - v} \alpha \text{ therefore } \eta[0 \rightarrow \alpha] \]

\[ P_w = \frac{\sigma_T - 3S_h + S_H + P_0}{(1 + \eta)} \]

"Impermeable:"

\[ \sigma_T = \sigma_{\theta\theta} = 3S_h - S_H - P_0 + P_w \]

\[ P_w = \sigma_T - 3S_h + S_H + P_0 \]

PMMA: \( v = 0.36; \alpha = 1? \)

Fluid pressure coefficient (tangential stress: permeable)

\[ \frac{1}{1 + \eta} \]

\[ 1 \]

\[ 0.5 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

Biot coefficient, alpha

H-W

H-F - Permeable

H-W impermeable
Entry Pressures into Borehole Wall

With and without borehole “membrane”

\[ \sigma_{\theta} = \pm S_H \frac{a^2}{r^2} (S_H = S_b) \]

Perforated or Unperforated

Unperforated membrane

\[ \sigma^p_{\theta} = -P_0 \frac{a^2}{r^2} \]

No fluid invasion

\[ p(3D) = -P_0 \frac{a}{r}; p(2D) = -P_0 \frac{\ln(r)}{\ln(a)} \]

Steady flow (3D, 2D)

\[ p = -P_0 \text{ Static invasion (no flow)} \]

If \( P_b(\text{impermeable}) > P_c > P_b(\text{permeable}) \):

\[ P_b(\text{impermeable}) \]

\[ P_c(\text{capillary entry pressure}) \]

\[ P_b(\text{permeable}) \]

Subcritical: scale with capillary entry pressure

Supercritical: scale with tensile strength

Water Saturation, \( S_w \)
Fluid Invasion – SubCrit/SuperCrit

Quantify breakdown pressure relationship with interfacial tension

**Super-critical (invasion):**
1. Pb dependent on tensile strength
2. Pb independent of interfacial tension

**Sub-critical (no-invasion):**

Invasion pressure scales with, $J$:

$$J = \frac{P_c \sqrt{k}}{\sigma} \approx \frac{\sqrt{k}}{\sigma}$$

**Quantify Breakdown Pressure**

**Breakdown Pressure vs Critical Temperature**

**Breakdown Pressure/Interfacial Tension vs Temperature**

Therefore:
1. Pb independent of tensile strength
2. Pb dependent on interfacial tension

$$\xi = \frac{P_b}{\sigma} = \frac{MPa}{mN/m} = \frac{10^6 N/m^2}{10^{-3} N/m} = \frac{10^9}{m}$$
Response for various capillary pressure magnitudes relative to tensile strength of the borehole wall - low stress regime.

Low $P_c$

$P_c < P_b(\text{perm})$

Intermediate $P_c$

$P_b(\text{imperm}) > P_c > P_b(\text{perm})$

High $P_c$

$P_c > P_b(\text{imperm})$
Modeling - Damage Mechanics

Microscopic-macroscopic model

Specimen geometry

[Lu et al., Computers and Geotechnics, 2013]
Initiation pressure (MPa)

Dynamic viscosity (Pa.s)

Water fracturing vs. gas fracturing

$P_{HW} = 8 \text{ MPa}$

$P_{HW} = 5.28 \text{ MPa}$

Compressible

Incompressible

Viscosity of Gas

Viscosity of Water

[Wang et al., ARMS8, 2014]
Modeling - Fracture Propagation

Driven by fluid pressure

Microcrack growth

Macrocrack growth
Modeling - Hydraulic fracturing with ideal gas

Gas fracturing (Compressible)

with the same material parameters of rock and pressurization rate

Water fracturing (Incompressible)

Confining stress ratio of 6:1

Confining stress ratio of 1:1
Shale gas is a significant resource and offers:
  Energy: Security, Independence and Environment
  Has a variety of water-related issues
  Waterless fracturing offers some advantages if understood

Advantages of gas fracturing
  Reduced water use
  Potential sequestration if GHG
  Generation of complex fracture networks
  Enhanced Shale Gas Recovery if CO₂

Experiments indicate some promise with behavior related to:
  Breakdown pressures related to gas state/type
  Fracture complexity related to gas state/type
    Supercritical N₂ more complex, He less complex... why?

Improved mechanistic understanding needed to fully utilize the promise of these observations

Integrated program across scales - Observation - Expt. - Analysis
Determine benefits:
  Feasibility/productivity/longevity
  Environment: Water consumption/protection and induced seismicity....