Shale Gas Production via Hydraulic Fracturing
AOSC 433/633 & CHEM 433
Ross Salawitch

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2015

- Overview of shale gas production via horizontal drilling and hydraulic fracturing (aka fracking)
- Concerns about shale gas production:
  - Earthquakes
  - Contamination of ground water
  - Air quality (surface O\textsubscript{3} precursors and PM\textsubscript{2.5})
  - Climate (fugitive release of CH\textsubscript{4})

Lecture 21
30 April 2015
Hydraulic Fracturing

- Pumping of chemical brine to loosen deposits of natural gas from shale
- Extraction of $\text{CH}_4$ from shale gas became commercially viable in 2002/2003 when two mature technologies were combined: horizontal drilling and hydraulic fracturing
- High-pressure fluid is injected into bore of the well at a pressure that fractures the rock

Proppant: solid material, typically treated sand or man-made ceramic materials, designed to keep an induced hydraulic fracture open.
Lower 48 Hydraulic Fracturing Geography

Source: Energy Information Administration based on data from various published studies.

http://photos.state.gov/libraries/usoecd/19452/pdfs/DrNewell-EIA-Administrator-Shale-Gas-Presentation-June212011.pdf

Copyright © 2015 University of Maryland
This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch.
US Fracking Map: 29 April 2015 Update

http://maps.fractracker.org/latest/?webmap=b26c43968bf8435388cbd4b33f2c4b3d
Pa Active Natural Gas Production


Copyright © 2015 University of Maryland
This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch.
Shale Gas Production

Dramatic Increase of U.S. Shale Gas Production
Billion Cubic Feet Per Day

<table>
<thead>
<tr>
<th>Year</th>
<th>% of US Total CH₄ Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>2</td>
</tr>
<tr>
<td>2006</td>
<td>6</td>
</tr>
<tr>
<td>2008</td>
<td>12</td>
</tr>
<tr>
<td>2011</td>
<td>29</td>
</tr>
<tr>
<td>2013</td>
<td>40</td>
</tr>
</tbody>
</table>

Note: LCI Energy Insight gross withdrawal estimates as of March 2013 and converted to dry production estimates with EIA-calculated average gross-to-dry shrinkage factors by state and/or shale play.

Source: EIA, U.S. Global Investors

Figure: http://www.usfunds.com/media/images/investor-alert/_2013/2013-12-13/COMM-Dramatic-Increase-US-Shale-Gas-Production-12132013-LG.gif
Shale Gas Production

Figure MT-44. U.S. natural gas production by source in the Reference case, 1990-2040

<table>
<thead>
<tr>
<th>Year</th>
<th>% of US Total CH₄ Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>2</td>
</tr>
<tr>
<td>2006</td>
<td>6</td>
</tr>
<tr>
<td>2008</td>
<td>12</td>
</tr>
<tr>
<td>2011</td>
<td>29</td>
</tr>
<tr>
<td>2013</td>
<td>40</td>
</tr>
</tbody>
</table>

Figure: http://www.usfunds.com/media/images/investor-alert/_2013/2013-12-13/COMM-Dramatic-Increase-US-Shale-Gas-Production-12132013-LG.gif
Shale Gas provides domestic source to meet U.S. consumer needs

U.S. dry gas trillion cubic feet per year

<table>
<thead>
<tr>
<th>Year</th>
<th>% of US Total CH₄ Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>2</td>
</tr>
<tr>
<td>2006</td>
<td>6</td>
</tr>
<tr>
<td>2008</td>
<td>12</td>
</tr>
<tr>
<td>2011</td>
<td>29</td>
</tr>
<tr>
<td>2013</td>
<td>40</td>
</tr>
</tbody>
</table>

Source: EIA, Annual Energy Outlook 2011

U.S. DOE 90 Day Shale Gas Subcommittee Interim Report (11 Aug 2011)
Tight Gas and Shale Gas

**Tight gas:** CH$_4$ dispersed within low porosity silt or sand that create “tight fitting” environment; has been extracted for many years using hydraulic fracturing.

**Shale gas:** CH$_4$ accumulated in small bubble like pockets within layers sedimentary rock such as shale, like tiny air pockets trapped in baked bread.

Shale Gas Production & Public Policy

- U.S. imports very little CH$_4$ (some imports from Canada)
- Price of CH$_4$ has fallen by a factor of 2 since 2008
- Concerns about shale gas production fall into four categories:
  - Earthquakes
  - Contamination of ground water
  - Air quality (surface O$_3$ precursors and PM$_{2.5}$)
  - Climate (fugitive release of CH$_4$)

- Former U.S. Dept of Energy Secretary David Chu (served 21 Jan 2009 to 22 April 2013) commissioned two reports from the Shale Gas Subcommittee of the Secretary of Energy Advisory Board (SEAB) to “identify measures that can be taken to reduce the environmental impact and to help assure the safety of shale gas production”

- First report (11 Aug 2011) identified 20 action items (see table, next slide)
- Second report (18 Nov 2011) outlined recommendations for implementation of action items
- EPA issued new standards for the oil and natural gas industry on 14 Jan 2015
- Notably absent is extended discussion of earthquake issue

http://www.epa.gov/airquality/oilandgas
First report (11 Aug 2011) identified 20 action items

1. Improve public information about shale gas operations
2. Improve communication among state and federal regulators
3. Improve air quality:
   4. Industry to measure CH₄ & other air pollutants
   5. Launch federal interagency effort to establish GHG footprint over shale gas extraction life cycle
   6. Encourage companies & regulators to reduce emissions using proven technologies & best practices
4. Protect water quality:
   8. Measure and report composition of water stock
   9. Manifest all transfers of water among different locations
   10. Adopt best practices for well casing, cementing, etc & conduct micro-seismic surveys to “assure that hydraulic growth is limited to gas producing formations”
   11. Field studies of possible CH₄ leakage from shale gas wells to water reservoirs
   12. Obtain background water quality measurements (i.e., CH₄ levels in nearby waters prior to drilling)

Protect water quality (cont.):
   13. Measure and report composition of water stock
   14. Disclosure of fracking fluid composition
   15. Reduce use of diesel fuel for surface power
   16. Manage short-term & cumulative impacts on communities & wild life: sensitive areas can be deemed off-limit to drilling and support infrastructure through an appropriate science based process
   17. Create shale gas industry organiz. to promote best practice, giving priority attention to:
      18. Air: emission measurement & reporting at various points in production chain
      19. Water: Pressure testing of cement casing & state-of-the-art technology to confirm formation isolation
   20. Increase R & D support from Administration & Congress to promote technical advances such as the move from single well to multiple-well pad drilling

Shale Gas Production & Public Policy

- First report (11 Aug 2011) identified 20 action items

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Improve public information about shale gas operations</td>
</tr>
<tr>
<td>2.</td>
<td>Improve communication among state and federal regulators</td>
</tr>
<tr>
<td>3.</td>
<td>Improve air quality:</td>
</tr>
<tr>
<td>4.</td>
<td>Industry to measure CH$_4$ &amp; other air pollutants</td>
</tr>
<tr>
<td>5.</td>
<td>Launch federal interagency effort to establish GHG footprint over shale gas extraction life cycle</td>
</tr>
<tr>
<td>6.</td>
<td>Encourage companies &amp; regulators to reduce emissions using proven technologies &amp; best practices</td>
</tr>
<tr>
<td>7.</td>
<td>Protect water quality:</td>
</tr>
<tr>
<td>8.</td>
<td>Measure and report composition of water stock</td>
</tr>
<tr>
<td>9.</td>
<td>Manifest all transfers of water among different locations</td>
</tr>
<tr>
<td>10.</td>
<td>Adopt best practices for well casing, cementing, etc &amp; conduct <a href="#">micro-seismic</a> surveys to “assure that hydraulic growth is limited to gas producing formations”</td>
</tr>
<tr>
<td>11.</td>
<td>Field studies of possible CH$_4$ leakage from shale gas wells to water reservoirs</td>
</tr>
<tr>
<td>12.</td>
<td>Obtain background water quality measurements (i.e., CH$_4$ levels in nearby waters prior to drilling)</td>
</tr>
</tbody>
</table>

Footnote 25:
Extremely small micro-earthquakes are triggered as an integral part of shale gas development. While essentially all of these earthquakes are so small as to pose no hazard to the public or facilities (they release energy roughly equivalent to a gallon of milk falling of a kitchen counter), earthquakes of larger (but still small) magnitude have been triggered during hydraulic fracturing operations and by the injection of flow-back water after hydraulic fracturing. It is important to develop a hazard assessment and remediation protocol for triggered earthquakes to allow operators and regulators to know what steps need to be taken to assess risk and modify, as required, planned field operations.

Shale Gas Production & Public Policy

- First report (11 Aug 2011) identified 20 action items

<table>
<thead>
<tr>
<th>Protect water quality (cont.):</th>
</tr>
</thead>
<tbody>
<tr>
<td>13. Measure and report composition of water stock</td>
</tr>
<tr>
<td>14. Disclosure of fracking fluid composition</td>
</tr>
<tr>
<td>15. Reduce use of diesel fuel for surface power</td>
</tr>
<tr>
<td>16. Manage short-term &amp; cumulative impacts on communities &amp; wildlife: sensitive areas can be deemed off-limit to drilling and support infrastructure through an appropriate science based process</td>
</tr>
<tr>
<td>17. Create shale gas industry organiz. to promote best practice, giving priority attention to:</td>
</tr>
<tr>
<td>18. Air: emission measurement &amp; reporting at various points in production chain</td>
</tr>
<tr>
<td>19. Water: Pressure testing of cement casing &amp; state-of-the-art technology to confirm formation isolation</td>
</tr>
<tr>
<td>20. Increase R &amp; D support from Administration &amp; Congress to promote technical advances such as the move from single well to multiple-well pad drilling</td>
</tr>
</tbody>
</table>

The Subcommittee shares the prevailing view that the risk of fracturing fluid leakage into drinking water sources through fractures made in deep shale reservoirs is remote. Nevertheless the Subcommittee believes there is no economic or technical reason to prevent public disclosure of all chemicals in fracturing fluids, with an exception for genuinely proprietary information. While companies and regulators are moving in this direction, progress needs to be accelerated in light of public concern.

Concern #1: Earthquakes

2012 Seismological Society of America meeting

ARE SEISMICITY RATE CHANGES IN THE MIDCONTINENT NATURAL OR MANMADE?


A remarkable increase in the rate of M 3 and greater earthquakes is currently in progress in the US midcontinent. The average number of M >= 3 earthquakes/year increased starting in 2001, culminating in a six-fold increase over 20th century levels in 2011. Is this increase natural or manmade? To address this question, we take a regional approach to explore changes in the rate of earthquake occurrence in the midcontinent (defined here as 85° to 108° West, 25° to 50° North) using the USGS Preliminary Determination of Epicenters and National Seismic Hazard Map catalogs. These catalogs appear to be complete for M >= 3 since 1970. From 1970 through 2000, the rate of M >= 3 events averaged 21 +/- 7.6/year in the entire region. This rate increased to 29 +/- 3.5 from 2001 through 2008. In 2009, 2010 and 2011, 50, 87 and 134 events occurred, respectively. The modest increase that began in 2001 is due to increased seismicity in the coal bed methane field of the Raton Basin along the Colorado-New Mexico border west of Trinidad, CO. The acceleration in activity that began in 2009 appears to involve a combination of source regions of oil and gas production, including the Guy, Arkansas region, and in central and southern Oklahoma. Horton, et al. (2012) provided strong evidence linking the Guy, AR activity to deep waste water injection wells. In Oklahoma, the rate of M >= 3 events abruptly increased in 2009 from 1.2/year in the previous half-century to over 25/year. This rate increase is exclusive of the November 2011 M 5.6 earthquake and its aftershocks. A naturally-occurring rate change of this magnitude is unprecedented outside of volcanic settings or in the absence of a main shock, of which there were neither in this region. While the seismicity rate changes described here are almost certainly manmade, it remains to be determined how they are related to either changes in extraction methodologies or the rate of oil and gas production.

Wednesday, April 18th / 3:45 PM Oral / Pacific Salon 4 & 5
Concern #1: Earthquakes

Ellsworth’s study area:

Concern #1: Earthquakes

Ellsworth’s study suggests:

▪ Deep waste water injection wells are the culprit, especially if in the vicinity of a fault
▪ Increased fluid pressure in pores of the rock can reduce the slippage strain between rock layers
▪ Speed of pumping is important (slow better than fast)

USGS testimony:

▪ On 19 June 2012, Dr. William Leath of the U.S. Geological Survey testified before the U.S. Senate Committee on Energy and Natural Resources, stating:

  The injection and production practices employed in these technologies have, to varying degrees, the potential to introduce earthquake hazards

  Since the beginning of 2011 the central and eastern portions of the United States have experienced a number of moderately strong earthquakes in areas of historically low earthquake hazard. These include M4.7 in central Arkansas on Feb 27, 2011; M5.3 near Trinidad, Colorado on Aug 23, 2011; M5.8 in central Virginia also on Aug 23, 2011; ... M5.6 in central Oklahoma on Nov 6, 2011 ... and M4.8 in east Texas on May 17, 2012. Of these only the central Virginia earthquake is unequivocally a natural tectonic earthquake.

  In all other cases, there is scientific evidence to at least raise the possibility that the earthquakes were induced by wastewater disposal or other oil- and gas-related activities.

  USGS scientists documented a seven-fold increase since 2008 in the seismicity of the central U.S., an increase largely associated with areas of wastewater disposal from oil, gas & coalbed methane production

First three bullets:
USGS testimony:
Concern #1: Earthquakes

28 Jan 2015 Washington Post

Oklahoma worries over swarm of earthquakes and connection to oil industry

2011 to 2013

Drilling waste water pumped underground, millions of barrels

Earthquakes magnitude 3 or larger

http://www.washingtonpost.com/graphics/national/oklahoma-earthquakes/
Concern #2: Water Quality


Copyright © 2015 University of Maryland
This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch.
Concern #2: Water Quality

Spread of contaminants in ground water determined by

Dispersion – differential flow of water through small openings (pores) in soil

Diffusion – random molecular (Brownian) motion of molecules in water

Sorption – some chemicals may be absorbed by soil while others are adsorbed (adhere to surfaces)

Highly diffusive chemicals (e.g. MTBE) can spread very quickly even though ground water is relatively motionless.

http://toxics.usgs.gov/topics/gwcontam_transport.html
Many chemicals used in fracking have “everyday” uses …

We control how chemicals are used in homes, not the case for fracking
Concern #2: Water Quality

April 2011: www.fracfocus.org created as central disclosure registry for industry use

Currently, official disclosure venue for 23 states

Searchable database & Google map interface allow user to obtain info for individual wells

Fluid composition:

http://fracfocus.org/welcome
**Concern #2: Water Quality**

April 2011: [www.fracfocus.org](http://www.fracfocus.org) created as central disclosure registry for industry use

Currently, official disclosure venue for 23 states

Searchable database & Google map interface allow user to obtain info for individual wells

### Fluid Composition

<table>
<thead>
<tr>
<th>Trade Name</th>
<th>Supplier</th>
<th>Purpose</th>
<th>Ingredients</th>
<th>Chemical Abstract Service Number (CAS #)</th>
<th>Maximum Ingredient Concentration in Additive (% by mass)**</th>
<th>Maximum Ingredient Concentration in HF Fluid (% by mass)**</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>(WFR-3B) Superior</td>
<td>Friction Reducer</td>
<td>Hydrotreated Light Distillate</td>
<td>64742-47-8</td>
<td>10.0 - 30.0%</td>
<td>0.17200%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mineral Spirits</td>
<td>8052-41-3</td>
<td>&lt; 10.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Propylene Glycol</td>
<td>57-55-6</td>
<td>&lt; 25.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ethoxylated Alcohols</td>
<td>68551-12-2</td>
<td>&lt; 4.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(KR-153SL) Superior</td>
<td>Biocide</td>
<td>2,2-Dibromo-3-nitriopropionamide</td>
<td>10222-01-2</td>
<td>20.0</td>
<td>0.02400%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Polyethylene Glycol</td>
<td>25322-68-3</td>
<td>50.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Diethylene Glycol</td>
<td>111-46-6</td>
<td>1.5 - 3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ethylene Glycol</td>
<td>107-21-1</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Super Scale Control TSC) Superior</td>
<td>Scale Inhibitor</td>
<td>Propylene Glycol</td>
<td>57-55-6</td>
<td>20.0 - 50.0%</td>
<td>0.05400%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 Phosphonobutane 1,2,4 Tricarboxylic Acid</td>
<td>37971-36-1</td>
<td>1.0 - 10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Anionic Copolymer</td>
<td>n/a</td>
<td>1.0 - 10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Anionic Polymer</td>
<td>n/a</td>
<td>1.0 - 10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(FE OXCLEAR) Superior</td>
<td>Oxygen Scavengar</td>
<td>Ammonium Bisulfite</td>
<td>10192-30-0</td>
<td>65.0 - 100%</td>
<td>0.09400%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand (Proppant) Superior</td>
<td>Propping Agent</td>
<td>Crystalline Silica</td>
<td>14808-60-7</td>
<td>99.90%</td>
<td>16.45000%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Provided by Customer</td>
<td>Base Fluid</td>
<td>Water</td>
<td></td>
<td>100.00%</td>
<td>83.21000%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fluid composition: Concern #2: Water Quality

April 2011: www.fracfocus.org created as central disclosure registry for industry use

Currently, official disclosure venue for 23 states

Searchable database & Google map interface allow user to obtain info for individual wells

Harvard Law School study highlights flaws in this system:

1) Timing of Disclosures: Site does not notify States if company submits late

2) Substance of Disclosure: Site does not provide state specific forms, no minimum reporting standards

3) Nondisclosures: Companies not required to disclose chemicals if they are considered a “trade secret”

~20% of all chemicals not reported.

Concern #2: Water Quality

Research in progress:

• Isotopic analysis of sites in Pennsylvania indicate levels of CH$_4$ in wells near (< 1km) drilling sites 17 times higher than sites further away, Osborn et al. (PNAS, 2011)

• Independent analysis of these sites suggests elevated CH$_4$ due to topography rather than fracking, Molofsky et al. (Oil Gas J., 2011), no evidence of fracking fluid in wells, Schon (PNAS, 2011)

• Surface water quality degraded through release from treatment facilities (increases Cl$^-$) and through release from wells (increases total suspended solids), Olmstead et al. (PNAS, 2012)
Concern #2: Water Quality

Research in progress:

• 12 March 2015 publication states CH₄ is present in drinking water, but is unrelated to proximity to wells

Methane Concentrations in Water Wells Unrelated to Proximity to Existing Oil and Gas Wells in Northeastern Pennsylvania

Donald L. Siegel, Nicholas A. Azzolina, Bert J. Smith, A. Elizabeth Perry, and Rikka L. Bothun

1Department of Earth Sciences, Syracuse University, 204 and 314 Heroy Geology Lab, Syracuse, New York 13244, United States
2The CETER Group, Inc., 1027 Faversham Way, Green Bay, Wisconsin 54313, United States
3Enviro Clean Products and Services, 11717 North Morgan Road, P.O. Box 721090, Yukon, Oklahoma 73172-1090, United States
4AECOM Technology Corporation, 250 Apollo Drive, Chelmsford, Massachusetts 01824, United States
5AECOM Technology Corporation, 1601 Prospect Parkway, Fort Collins, Colorado 80525, United States

Supporting Information

http://pubs.acs.org/doi/abs/10.1021/es505775c

Article received a commentary in Science:
http://news.sciencemag.org/environment/2015/03/methane-drinking-water-unrelated-fracking-study-suggests
Concern #3: Air Quality (Case Study: Wyoming)

Ozone: Wintertime Phenomenon

\[ \text{NOx + VOC = Ozone} \]

Sunlight
Little Wind
Snow Cover
Inversion

Sunlight and Reflection

Emitted VOC and NOx

http://deq.state.wy.us/out/downloads/UGRBTaskForce02212012WDEQAQD.pdf
Concern #3: Air Quality (Case Study: Wyoming)

2011 Preliminary Data (as of 3/20/2011)

10 Advisory Days
- February 28
- March 1, 2, 4, 5, 10, 13, 14, 15, 18

13 Elevated 8-Hour Ozone Days
- February 14, 15, 21
- March 1, 2, 3, 5, 6, 9, 10, 12, 14, 15

<table>
<thead>
<tr>
<th>2011 Preliminary Raw Data (as of 3/20/2011)</th>
<th>Monitored Ozone Top Four 8-Hour Daily Maximum (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>84</td>
<td>90</td>
</tr>
<tr>
<td>81</td>
<td>84</td>
</tr>
<tr>
<td>80</td>
<td>81</td>
</tr>
<tr>
<td>73</td>
<td>77</td>
</tr>
</tbody>
</table>

NOTE: Three (3) year average of 4th high 8-Hour Daily Maximum is compared to NAAQS.

http://deq.state.wy.us/out/downloads/March22PublicMtg_2011Ozone_WDEQ.pdf
Concern #3: Air Quality (Case Study: Wyoming)

Sublette County Ozone & Weather History (2005 – 2011)

- **Mid-January – March 2005**
  - 8 Elevated 8-Hour O₃ Days > 75 ppb

- **Mid-January – March 2006**
  - 2 Elevated 8-Hour O₃ Days > 75 ppb

- **Mid-January – March 2007**
  - 0 Elevated 8-Hour O₃ Days > 75 ppb
  - Meteorological conditions not conducive to formation of elevated ozone levels.

- **Mid-January – March 2008**
  - 14 Elevated 8-Hour O₃ Days > 75 ppb
  - Higher magnitude than previous years
  - Met. conditions conducive to formation of elevated ozone levels.

- **Mid-January – March 2009**
  - 0 Elevated 8-Hour O₃ Days > 75 ppb
  - Limited met. conditions conducive to formation of elevated ozone levels.

- **Mid-January – March 2010**
  - 0 Elevated 8-Hour O₃ Days > 75 ppb
  - Met. conditions not conducive to formation of elevated ozone levels.

- **Mid-January – March 2011**
  - 13 Elevated 8-Hour O₃ Days > 75 ppb
  - Higher magnitude than previous years
  - Met. conditions conducive to formation of elevated ozone levels.

http://deq.state.wy.us/out/downloads/March22PublicMtg_2011Ozone_WDEQ.pdf
Concern #3: Air Quality (Case Study: Wyoming)

Sublette County Winter Inventory
Daily NOx Emissions

- O&G On-Road Mobile
- O&G Non-Road Mobile
- Venting & Blowdowns
- Completions
- Drill Rigs
- Stationary Engines
- Pneumatic Pumps
- Dehys
- Tanks
- Process Heaters

Concern #3: Air Quality (Case Study: Wyoming)

Sublette County Winter Inventory
Daily VOC Emissions

- O&G On-Road Mobile
- O&G Non-Road Mobile
- Venting & Blowdowns
- Completions
- Drill Rigs
- Stationary Engines
- Pneumatic Pumps
- Dehys
- Tanks
- Process Heaters

Concern #3: Air Quality (Case Study: Wyoming)

Tropospheric Ozone Production versus NO$_x$ and VOCs

Figure: [http://www-personal.umich.edu/~sillman/ozone.htm](http://www-personal.umich.edu/~sillman/ozone.htm)
Concern #3: Air Quality (Case Study: Maryland)

- Air mass trajectories (meteorological modeling) show air parcels affected by fracking can reach the Baltimore/DC region.
- Fracking releases a stew of VOCs, including ethane (C\textsubscript{2}H\textsubscript{6}).
- Ethane and other VOCs measured at Essex MDE site.

MDE’s Air Monitoring Network

- 22 Monitoring stations.
- 37 Trace gas monitors.
  - O\textsubscript{3}, CO, SO\textsubscript{2}, NO\textsubscript{2}, NO\textsubscript{y}
- 38 aerosol monitors.
- 2 sites collecting ozone precursor VOCs.
- 2 sites collecting 58 toxic species.
- 12 sites collect meteorological.
Concern #3: Air Quality (Case Study: Maryland)

• Air mass trajectories (meteorological modeling) show air parcels affected by fracking can reach the Baltimore/DC region

• Fracking releases a stew of VOCs, including ethane ($C_2H_6$)

• Ethane and other VOCs measured at Essex MDE site

Vinciguerra et al., Atmospheric Environment, 2015
Concern #4: Climate

As shown in Lecture 18, under normal operating conditions w/ no leaks, less CO$_2$ is released to the atmosphere per kWh if gas (CH$_4$) is used to generate electricity than if coal is used to generate the equivalent amount of electricity:

Since CH$_4$ has a larger GWP than CO$_2$, if CH$_4$ escapes via leakage rather than being oxidized via combustion, the **net GWP** of the sum of rising atmospheric CH$_4$ due to leakage plus rising CO$_2$ following combustion of natural gas can exceed the GWP of CO$_2$ from the combustion of fossil fuel.

<table>
<thead>
<tr>
<th>Fossil Fuel</th>
<th>GHG Output (pounds CO$_2$ per kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Sands</td>
<td>5.6</td>
</tr>
<tr>
<td>Coal</td>
<td>2.1</td>
</tr>
<tr>
<td>Oil</td>
<td>1.9</td>
</tr>
<tr>
<td>Gas</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Concern #4: Climate

Modeling of Shale Gas Production

A. 20-year time horizon

Table 2  Fugitive methane emissions associated with development of natural gas from conventional wells and from shale formations (expressed as the percentage of methane produced over the lifecycle of a well)

<table>
<thead>
<tr>
<th></th>
<th>Conventional gas</th>
<th>Shale gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions during well completion</td>
<td>0.01%</td>
<td>1.9%</td>
</tr>
<tr>
<td>Routine venting and equipment leaks at well site</td>
<td>0.3 to 1.9%</td>
<td>0.3 to 1.9%</td>
</tr>
<tr>
<td>Emissions during liquid unloading</td>
<td>0 to 0.26%</td>
<td>0 to 0.26%</td>
</tr>
<tr>
<td>Emissions during gas processing</td>
<td>0 to 0.19%</td>
<td>0 to 0.19%</td>
</tr>
<tr>
<td>Emissions during transport, storage, and distribution</td>
<td>1.4 to 3.6%</td>
<td>1.4 to 3.6%</td>
</tr>
<tr>
<td>Total emissions</td>
<td>1.7 to 6.0%</td>
<td>3.6 to 7.9%</td>
</tr>
</tbody>
</table>

Howarth et al., Climatic Change, 2011
Concern #4: Climate

Criticism of Modeling of Shale Gas Production

Cathles et al. believe Howarth et al.’s argument fails on four critical points:

1) The 7.9% upper limit for CH₄ leakage from well drilling exceeds a reasonable upper limit by about a factor of 3

2) Importance of rapidly improving technology to reduce fugitive CH₄ emissions is dismissed

3) Study places undue emphasis on 20 yr time horizon:
   As Pierrehumbert (2011) explains, “Over the long term, CO₂ accumulates in the atmosphere like mercury in the body of a fish, whereas CH₄ does not. For this reason, it is the CO₂ emissions, and the CO₂ emissions alone, that determine the climate that humanity will need to live with.”

4) CH₄ end use for heating is compared to coal end use for electricity generation:
   “Electric industry has large stock of old, inefficient coal-fired electric generating plants that could be considered for replacement by natural gas … The much lower construction costs associated with gas power plants means modern gas technology will likely replace this old coal technology as it is retired. If total (well drilling to delivery) leakage is limited to less than 2% (which may be the current situation …) switching from coal to natural gas would dramatically reduce the greenhouse impact of electricity generation.”

Cathles III et al., Climatic Change, 2012
Concern #4: Climate

Criticism of Modeling of Shale Gas Production

Cathles et al. believe Howarth et al.’s argument fails on four critical points:

1) The 7.9% upper limit for CH₄ leakage from well drilling exceeds a reasonable upper limit by about a factor of 3

2) Importance of rapidly improving technology to reduce fugitive CH₄ emissions is dismissed

3) Study places undue emphasis on 20 yr time horizon

4) CH₄ end use for heating is compared to coal end use for electricity generation

Cathles III et al., *Climatic Change*, 2012
Observed fugitive CH$_4$ emissions

Karion et al. report leakage of 9% (6.2 to 11.7% range) of CH$_4$ from a field study in the Uinta Basin Utah, nearly double the cumulative loss rates estimated from industry data.

Karion et al, GRL, 2013

**Equation 1:**

\[
\text{flux}_{\text{CH}_4} = V \int_{-b}^{b} X_{\text{CH}_4}(z) \left( \int_{z_{\text{ground}}}^{z_{\text{PBL}}} n_{\text{air}} \, dz \right) \cos \theta \, dx
\]
Concern #4: Climate

Observed fugitive CH₄ emissions

Howarth et al, ESE, 2014