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The Science of Shale Gas: The Latest Evidence on Leaky Wells, Methane Emissions, and Implications for Policy

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Cornell University
and
Physicians, Scientists, and Engineers for Healthy Energy, Inc.

Youngstown State University
March 26, 2014
"It is just business as usual, fracking has been around for 60 years, no new concerns." (My Nov. 2012 Talk)

“The methane in private water wells was always there: we did not do it. With 4 or more layers of steel casing and cement barriers, our wells do not leak.”

“Methane is a clean fossil fuel. Methane is a cleaner fossil fuel. Methane is the bridge fuel to a green renewable energy future.”
Shale Gas/Oil Production Must Use Clustered, Multi-Well Pads and High-Volume Long Laterals

Because GEOLOGY RULES: Permeability, Depth, Thickness, Thermal Maturity, Total Organic Carbon

Photo: Chesapeake / Statoil
“The methane in private water wells was always there: we did not do it. With 4 or more layers of steel casing and cement barriers, our wells do not leak.”

**Part 1 of My Talk:** “Leaking wells” is a chronic, ubiquitous, well-understood problem. It is unresponsive to “tough regulation”. It is causing contamination of drinking water at an increasing rate.
There are at least three possible mechanisms for fluid migration into the shallow drinking-water aquifers that could help explain the increased methane concentrations we observed near gas wells…A second mechanism is leaky gas-well **casings**…Such leaks could occur at hundreds of meters underground, with methane passing laterally and vertically through fracture systems.”

From Osborn et al. PNAS, 2011
A leaking gas/oil well may cause contamination of drinking water sources and/or methane emissions to the atmosphere. This is an example of “Sustained Annular Flow”.

Absence of evidence of bubbling is not evidence of absence of leaking. This could be result of cement failure, or casing failure. How common are such failures?

Video courtesy PA DEP
Industry-Reported Data On Loss of Wellbore Integrity: Offshore Wells

SCP=Sustained Casing Pressure. Also called sustained annular pressure, in one or more of the casing annuli.

- About 5% of wells fail soon
- More fail with age
- Most fail by maturity

Wells with SCP by age. Statistics from the United States Mineral Management Service (MMS) show the percentage of wells with SCP for wells in the outer continental shelf (OCS) area of the Gulf of Mexico, grouped by age of the wells. These data do not include wells in state waters or land locations.

Brufatto et al., Oilfield Review, Schlumberger, Autumn, 2003
Industry-Reported Data On Loss of Wellbore Integrity: Onshore Wells

Watson and Bachu, SPE 106817, 2009.
Industry well integrity outlook

- Industry will drill more wells in next decade than have been drilled in last 100 years
- Global well population is +/- 1.8 million, of which +/- 35% has sustained casing pressure
- Public awareness and concern of zonal isolation requirements is increasing (USA / Australia / Europe)
- Geothermal wells and CO2 sequestration wells are on the increase
- Subsidence is a risk in some depleting reservoirs
- Life cycle extension of aging assets is becoming a pre-requisite of legislators
- Zonal isolation challenges and assurance does need push in technology
- Abandonment of legacy wells is becoming more of a focus
- Industry collaboration is an inevitable pre-requisite on all topics
Leaky Well Industry Statistics

Well Life Prior to Leak, Years

From George E King Consulting Inc.: http://gekengineering.com/id6.html
Gas leaks from shale wells rare

Not exactly a peer-reviewed source of information
So, We Decided To Do Our Own Study*

- 8,703 wells show no public record of inspection; 5,223 wells with erroneous spud or inspection dates: all removed from further study

Resulting modeled statewide dataset contains **27,455 wells and 75,505 inspections**.

- Mined the data to identify all wells with wellbore integrity problems
- Statistically analyzed results: Cox Proportional Hazard Model
- Not-Yet-Published results presented here

Integrity Problem Indicators

Search Procedure: Three Filters

• Filter database for entries in “Violation Code” or “Violation Comment” fields in inspection reports for Notice of Violation (NOV).

• Filter both the “Inspection Comment” and “Violation Comment” fields for most common keywords associated with failure of primary cement/casing or common remediation measures: leaking well without NOV.

• Keyword filter results then human-read thoroughly to confirm an indication of impaired well integrity: verify software filter.
<table>
<thead>
<tr>
<th>Violation Code (#)</th>
<th>Notice of Violation Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>78.83GRNDWTR (76)</td>
<td>Improper casing to protect fresh groundwater</td>
</tr>
<tr>
<td>78.83COALCSG (12)</td>
<td>Improper coal protective casing and cementing procedures</td>
</tr>
<tr>
<td>78.81D1 (1)</td>
<td>Failure to maintain control of anticipated gas storage reservoir pressures while drilling through reservoir or protective area</td>
</tr>
<tr>
<td>207B (11)</td>
<td>Failure to case and cement to prevent migrations into fresh groundwater</td>
</tr>
<tr>
<td>78.85 (1)</td>
<td>Inadequate, insufficient, and/or improperly installed cement</td>
</tr>
<tr>
<td>78.86 (101)</td>
<td>Failure to report defective, insufficient, or improperly cemented casing w/in 24 hours or submit plan to correct w/in 30 days</td>
</tr>
<tr>
<td>78.81D2 (4)</td>
<td>Failure to case and cement properly through storage reservoir or storage horizon</td>
</tr>
<tr>
<td>78.73A (21)</td>
<td>Operator shall prevent gas and other fluids from lower formations from entering fresh groundwater.</td>
</tr>
<tr>
<td>78.73B (81)</td>
<td>Excessive casing seat pressure</td>
</tr>
<tr>
<td>78.84 (2)</td>
<td>Insufficient casing strength, thickness, and installation equipment</td>
</tr>
<tr>
<td>209CASING (1)</td>
<td>Using inadequate casing</td>
</tr>
<tr>
<td>210NCPLUG (1)</td>
<td>Inadequate plugging of non-coal well above zones having borne gas, oil, or water</td>
</tr>
<tr>
<td>78.83A (2)</td>
<td>Diameter of bore hole not 1 inch greater than casing/casing collar diameter</td>
</tr>
<tr>
<td>210INADPLUG (1)</td>
<td>Leaking plug or failure to stop vertical flow of fluids</td>
</tr>
<tr>
<td>79.12 (2)</td>
<td>Inadequate casing/cementing in conservation well</td>
</tr>
<tr>
<td>78.82 (1)</td>
<td>Remove conductor pipe</td>
</tr>
</tbody>
</table>

(Source: PADEP (2013a))
## Indicator Keywords and Descriptions Used in 2nd Filter

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Description</th>
<th>Keywords/phrasing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement Squeeze (34)</td>
<td>Remedial cementing operation performed to repair poor primary cement jobs, repair damaged casing or liner, or isolate perforations. Any squeeze job, not related to plugging activities, is assumed to be indicator of loss of containment.</td>
<td>“squeeze”, “squeeze*”, “eeze”, “perf and patch”, “perf”</td>
</tr>
<tr>
<td>Top Job (13)</td>
<td>Remedial cementing operation used to bring cement up to surface in the event of a cement drop following primary cementing. Documented top jobs are assumed to be an indicator of loss of primary cement integrity.</td>
<td>“top job”, “topped off”, “cement drop*”, “cement fall”, “cement not to surface&quot;</td>
</tr>
<tr>
<td>Annular Gas (20)</td>
<td>Gas/methane detected within an annulus, whether in an annular vent or otherwise, indicates a loss of subsurface integrity. Combustible gas or lower explosive limit (LEL) readings off of vents or annuli and indications of gas detected from annular vents are assumed to indicate loss of containment.</td>
<td>“LEL”, “comb*”, “annular gas”, “annular vent”</td>
</tr>
<tr>
<td>SCP (69)</td>
<td>Sustained Casing Pressure</td>
<td>“bubbling”, “bubbl*”, “bleed”, “bled down”</td>
</tr>
<tr>
<td>Other (9)</td>
<td>Additional phrasing relevant to primary cement job failure or casing corrosion was also searched and assessed according to inspection history and the other information contained within each inspection’s comments.</td>
<td>“remediation”, “recement”, “cement fail*”, “casing fail*”, “casing patch”, “Improper casing”, “improper cement”, “gas migration”, “gas leak*”</td>
</tr>
</tbody>
</table>

* Indicates a wildcard search
## Wells With Indicators, Statewide

<table>
<thead>
<tr>
<th>Spud Year</th>
<th>Conventional Wells</th>
<th>Unconventional Wells</th>
<th>Statewide Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Indicator</td>
<td>Inspected</td>
<td>%</td>
</tr>
<tr>
<td>2000</td>
<td>5</td>
<td>1389</td>
<td>0.40%</td>
</tr>
<tr>
<td>2001</td>
<td>10</td>
<td>1827</td>
<td>0.50%</td>
</tr>
<tr>
<td>2002</td>
<td>10</td>
<td>1564</td>
<td>0.60%</td>
</tr>
<tr>
<td>2003</td>
<td>17</td>
<td>1940</td>
<td>0.90%</td>
</tr>
<tr>
<td>2004</td>
<td>14</td>
<td>2308</td>
<td>0.60%</td>
</tr>
<tr>
<td>2005</td>
<td>22</td>
<td>2949</td>
<td>0.70%</td>
</tr>
<tr>
<td>2006</td>
<td>42</td>
<td>3307</td>
<td>1.30%</td>
</tr>
<tr>
<td>2007</td>
<td>28</td>
<td>3461</td>
<td>0.80%</td>
</tr>
<tr>
<td>2008</td>
<td>34</td>
<td>3337</td>
<td>1.00%</td>
</tr>
<tr>
<td>2009</td>
<td>17</td>
<td>1620</td>
<td>1.00%</td>
</tr>
<tr>
<td>2010</td>
<td>16</td>
<td>1345</td>
<td>1.20%</td>
</tr>
<tr>
<td>2011</td>
<td>48</td>
<td>1055</td>
<td>4.50%</td>
</tr>
<tr>
<td>2012</td>
<td>17</td>
<td>813</td>
<td>2.10%</td>
</tr>
<tr>
<td>SUM</td>
<td>280</td>
<td>26915</td>
<td>1.0%</td>
</tr>
</tbody>
</table>
Well Failure Rate Analysis

- **Cox Proportional Hazard Model** to model well failure (hazard) rate
- A multivariate regression technique to model the instantaneous risk of observing an event at time $t$ given that an observed case has survived to time $t$, as a function of predictive covariates.
- Well type (i.e. unconventional or conventional) and inspection counts (i.e. the number of times a well is inspected during the analysis time) are used as covariates.
- Spud year cut-off (pre- and post-2009) and geographic (i.e. county) strata are run in separate analyses.
- Inter-annual Wilcoxon statistics used to assess whether any groups of well spuds were statistically significantly different in terms of their predicted failure risk.
- **Risk of cement/casing problems** for wells with incomplete inspection histories can be estimated from the behavior of wells with more complete histories.
Unconventional wells show a 58% (95%CI [47.3%, 67.2%]) higher risk of experiencing structural integrity issues relative to conventional wells.
Hazard Prediction for Northeast and Non-Northeast Counties: All Wells

Fractional Probability of Loss of Zonal Isolation

Bradford, Cameron, Clinton, Lycoming, Potter, Sullivan, Susquehanna, Tioga, Wayne, and Wyoming = Northeast

analysis time (weeks)
Hazard Prediction for Northeast PA Counties, Pre- and Post-2009 Spuds

Fractional Probability of Loss of Zonal Isolation

- Analysis time (weeks)
  - pre 2009
  - post 2009
Observations and Implications

• Cement/casing failure is chronic and well-known mode of loss of wellbore integrity.
• Thorough analysis of well integrity data in “modern” shale wells under “tough” regulations indicates significant failure rate continues.
• Support for hypothesis that methane migration incidents are resulting from “leaky” wells.
• With **30-40,000 shale gas/oil wells per year expected in the U.S. over the next decade**, many contamination incidents likely to occur.
“Methane is a clean fossil fuel. Methane is a cleaner fossil fuel. Methane is the bridge fuel to a green renewable energy future.”

**Part 2 of My Talk:** Methane is not a clean fossil fuel: no such thing. Methane is not a cleaner fossil fuel: it is the dirtiest from a climate change perspective. It is not a bridge: it is a gangplank.
CO$_2$ Concentration in the Atmosphere

Seasonal fluctuation

Rate-of-increase:
~ 2 ppm/year

http://www.esrl.noaa.gov/gmd/ccgg/trends/
Measured **Methane** Concentration in the Atmosphere: Recent Record

courtesy of Ed Dlugokencky, NOAA. February 2014
Large-Scale Shale Gas Production Creates 3 Major Climate Problems

• Produces CO$_2$ when it is burned
• Methane, CH$_4$, leaked or purposefully vented:
  - During drilling
  - During initial frac fluid flow-back period
  - Continuously at the pad site via leaking wells
  - During liquid unloading
  - During gas processing
  - During transmission, storage, and distribution
• Produces black carbon, BC, (soot) during flaring and processing
There Are Three Key Questions:

• A Technology Question: How much methane is being emitted by oil/gas operations?
• A Science Question: What is impact on climate change of methane emissions?
• A Policy Question: Over what period of time should we measure that impact?
Upstream/Midstream Methane Emission Measurements are Coming in Very High Relative to EPA Estimate of 1.8%

Uinta Basin, Utah:
Up to 9% of total production

Denver–Julesburg Basin, Colorado:
2.3% to 7% of total production

Los Angeles Basin, California
~ 17% of total production but includes natural seeps
Flyover Box for Upstream/Midstream Methane Flux Measurements from Active Marcellus Drilling Area
Regional Enhancement of Methane at 250 m AGL on the morning of June 20th, 2012

a. Drill rig
b. Unlit but venting flare stack
c. Air compressors
d. Main high-pressure air line
e. Flow line
f. Separator unit
g. Water tanks
### Natural Gas Portion of the Top-Down Flux as a Percentage of Natural Gas Production

<table>
<thead>
<tr>
<th></th>
<th>18 hour Estimate</th>
<th>5-6 hour Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Top-Down Flux</strong></td>
<td>3.1 g CH$_4$s$^{-1}$km$^{-2}$</td>
<td>10.3 g CH$_4$s$^{-1}$km$^{-2}$</td>
</tr>
<tr>
<td><strong>CH$_4$ from Nat. Gas</strong></td>
<td>22%</td>
<td>62%</td>
</tr>
<tr>
<td><strong>Nat. Gas Prod. Rate</strong></td>
<td>15.9 g CH$_4$s$^{-1}$km$^{-2}$</td>
<td>50.1 g CH$_4$s$^{-1}$km$^{-2}$</td>
</tr>
<tr>
<td><strong>Nat. Gas Flux/ Prod. Rate</strong></td>
<td><strong>4.3%</strong></td>
<td><strong>12.1%</strong></td>
</tr>
</tbody>
</table>

Downstream Methane Leakage from Aging Urban Distribution Pipelines: Boston MA

Natural background level is about 1.9 ppm
Washington, D.C., had 5,893 pipeline leaks across 1,500 road miles of the city.

Jackson et al. Natural Gas Pipeline Leaks Across Washington, DC. ES&T, 2014
“Results show that current inventories from the US Environmental Protection Agency (EPA) and the Emissions Database for Global Atmospheric Research (EDGAR) underestimate methane emissions nationally by a factor of ∼1.5 and ∼1.7, respectively.”

“The results indicate that drilling, processing, and refining activities over the south-central United States have emissions as much as 4.9 ± 2.6 times larger than EDGAR.”

“The US EPA recently decreased its CH₄ emission factors for fossil fuel extraction and processing by 25–30% (for 1990–2011), but we find that CH₄ data from across North America instead indicate the need for a larger adjustment of the opposite sign.”
"Removing sources that are known not to be in the GHGI, but measured in atmospheric observations (wild ruminants, and termites) the unexplained excess decreases to 6.8 to 20.8 Tg CH4/year, or yields an excess percentage leakage of 1.8% to 5.4% of end use gas. Coupled with the current estimate of 1.8% leakage of end use gas consumed, this generates a high-end estimate of 7.1% gas leakage (on an end use basis). This worst-case scenario is unlikely: it would require all excess CH4 to come from the NG industry, and require total excess at the high end of the observed range from national-scale studies."

This looks like a leakage rate range of 3.6% to 7.1%, say 5.4% +/- 1.8%.

Howarth, Santoro, Ingraffea predicted a total leakage range of 3.6% to 7.9%. Climatic Change Letters, 2011.
There Are Three Key Questions:

• A Technology Question: How much methane is being emitted by oil/gas operations?
• A Science Question: What is impact on climate change of methane emissions?
• A Policy Question: Over what period of time should we measure that impact?
Methane Is a Much More Potent Greenhouse Gas Than Carbon Dioxide

• Up to 34 times more potent over 100 years*
• Up to 86 times more potent over 20 years*
• Therefore, even small leakage rates important:
  Over 20 years, each 1% lifetime production leakage from a well produces nearly the same climate impact as burning the methane twice.

*IPCC AR5, October, 2013
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, Ingraffea, NATURE, 477, 2011
That 3.2% Number


Claims 3.2% to be the immediate, average break-even leak rate for climate benefit of methane over coal for electricity generation
Methane a Winner for Electricity Generation, If….

Years Until Net Climate Benefit Achieved

Coal power plant

Percent Natural Gas Leakage

0 0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0

0 20 40 60 80 100

3.2 %
What Happens When Science Overtakes That Number? When Constrained by Policy?

Maximum Gas Leak Rate, %

Years to Net Climate Benefit

- Alvarez et al., 2012, pre-IPCC AR 5
- Present Study, 2014, post-IPCC AR 5

- 3.2%
- 2.7%
To Estimate Risk, One Needs to Know Uncertainty

We have a situation where we need to know a small, uncertain number whose impact is highly sensitive to a small error in its estimation. And then we need policy that quantifies risk. Yikes!!!!
“Assessments using 100-year impact indicators show system-wide leakage is unlikely to be large enough to negate climate benefits of coal-to-NG substitution.”

“Fortunately for gas companies, a few leaks in the gas system probably account for much of the problem and could be repaired.”

Emphases mine.
Why Is Controlling Methane (CH$_4$) Emission So Important?

Here is the U.S. Energy Information Agency Forecast

Figure 7. U.S. primary energy consumption by fuel, 1980-2040 (quadrillion Btu per year)
“I also find a troubling inconsistency in the notion that, as an investor, we should boycott a whole class of companies at the same time that, as individuals and as a community, we are extensively relying on those companies’ products and services for so much of what we do every day. Given our pervasive dependence on these companies for the energy to heat and light our buildings, to fuel our transportation, and to run our computers and appliances, it is hard for me to reconcile that reliance with a refusal to countenance any relationship with these companies through our investments.”

The Faculty Senate of Cornell agrees! So….
The Cornell Faculty Senate Resolution: Overwhelmingly Approved, 12/11/2013

Therefore be it resolved that Cornell faculty, responsible university offices and officials should seek a more aggressive reduction in the use of fossil fuels that will achieve carbon neutrality by 2035.

Be it further resolved that Cornell investments in companies producing such fuels be reduced in proportion to Cornell’s progress towards carbon neutrality so as to achieve full divestment by 2035.

Be it further resolved that this should be done by a schedule that prioritizes divestment from those companies holding the largest fossil fuel reserves;

Be it further resolved that the President of Cornell will submit an annual report to the Faculty Senate describing the progress that the University has made in becoming carbon neutral and divesting from companies holding the largest fossil fuel reserves.

https://drive.google.com/folderview?id=0B5rAADI0L4DicXhmdjZEdkVqWmc&usp=sharing
Thank You for Attending and Participating Tonight

http://www.psehealthyenergy.org/site/view/1180