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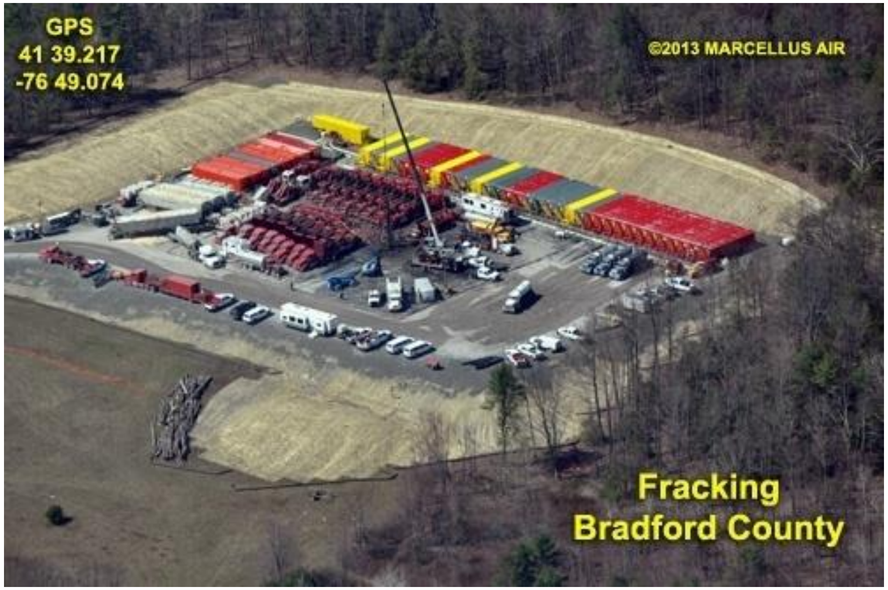
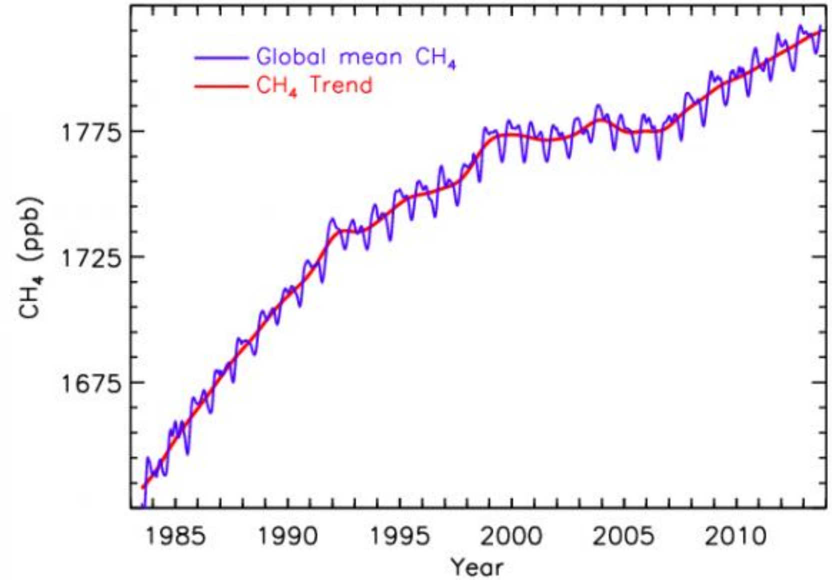




The Science of Shale Gas: The Latest Evidence on Leaky Wells, Methane Emissions, and Implications for Policy

A. R. Ingraffea

Dwight C. Baum Professor

Cornell University

and

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

Youngstown State University

March 26, 2014

From the Supporters of Increased Development of <u>Shale</u> Gas/NGL/Oil

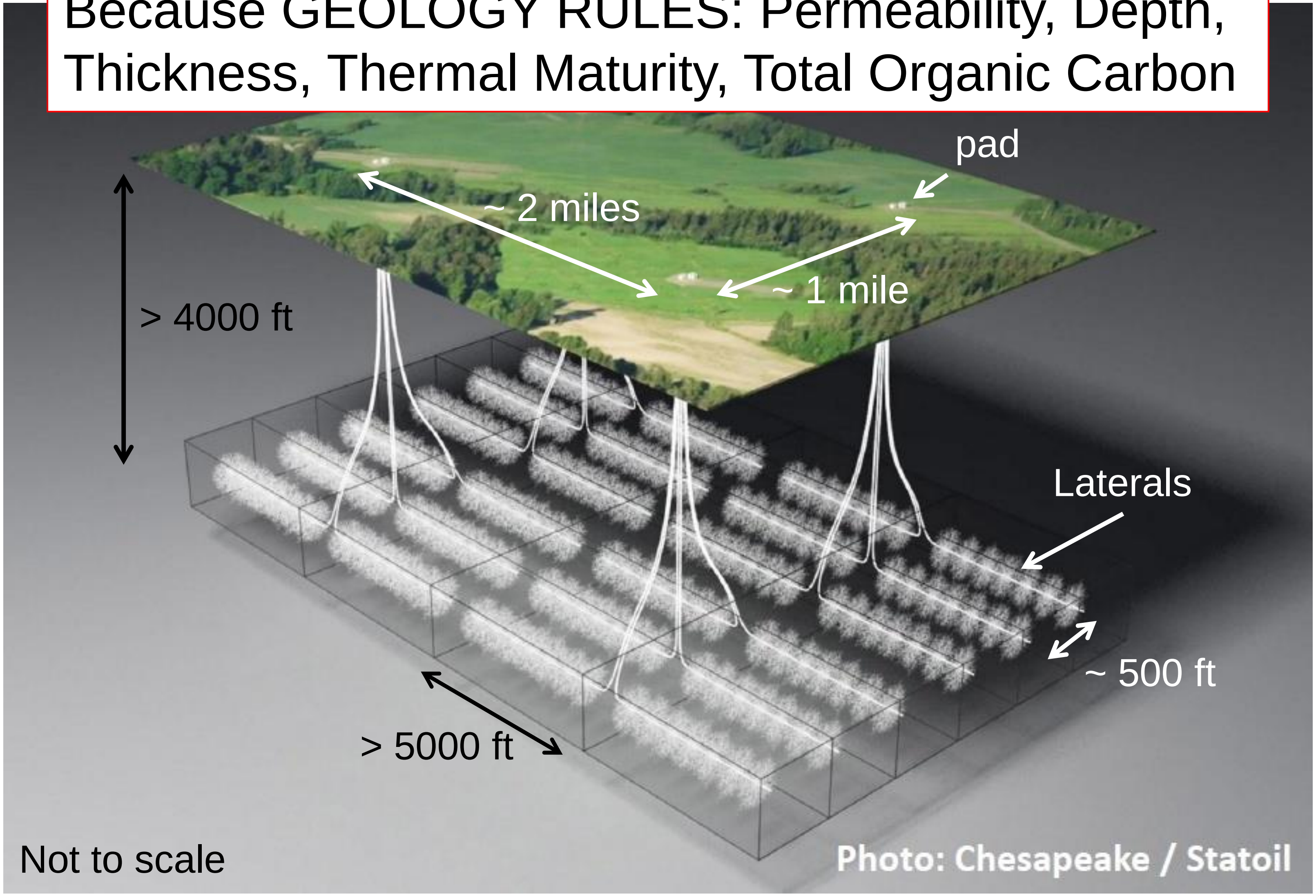
"It is just business as usual, fracking has been around for 60 years, no new concerns." *(My Nov. 2012 Talk)*

"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

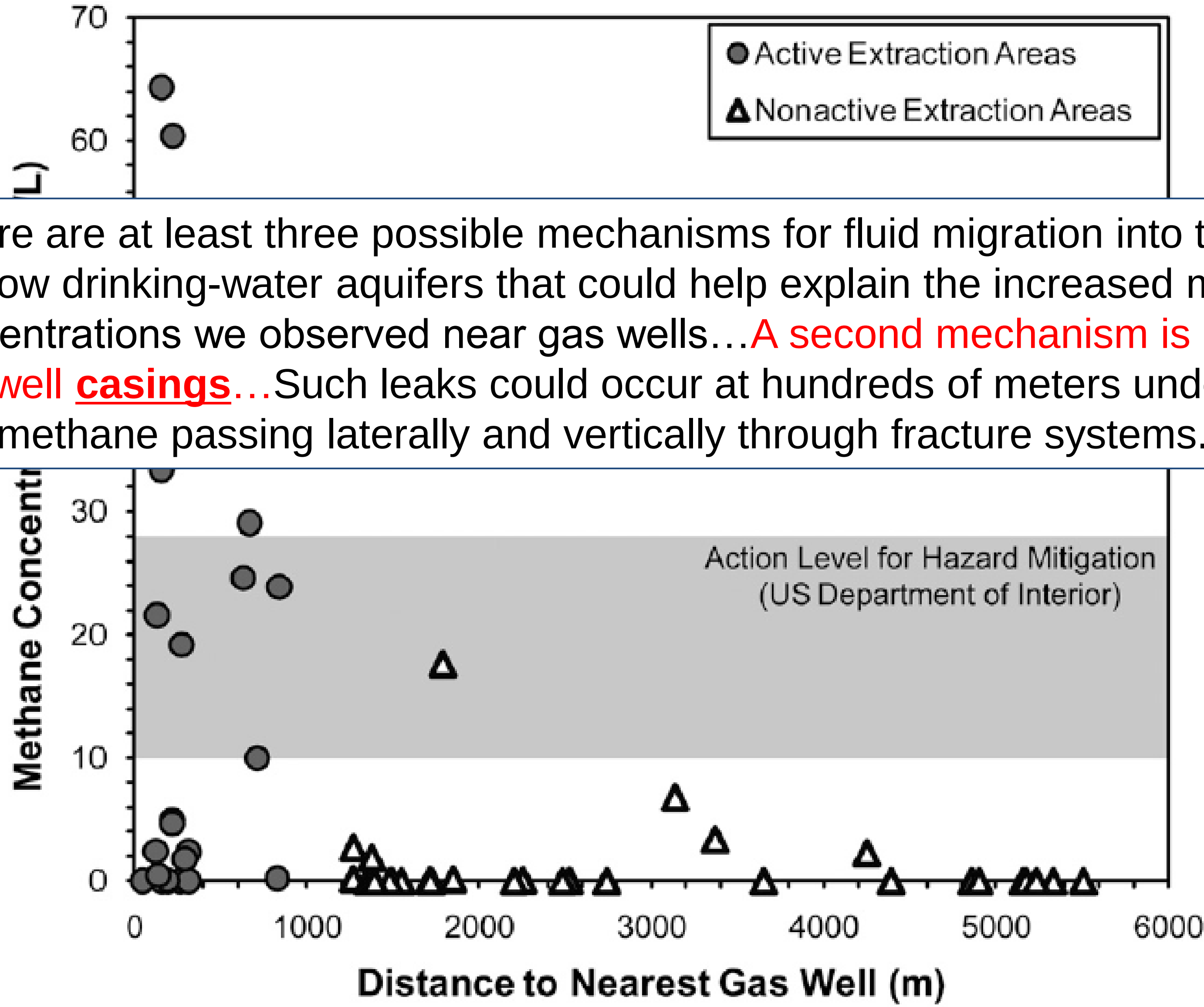


Why NOT More Shale Gas/NGL/Oil?

"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.

Source of Methane Migration into Groundwater? Hundreds of Private Water Wells Contaminated in PA

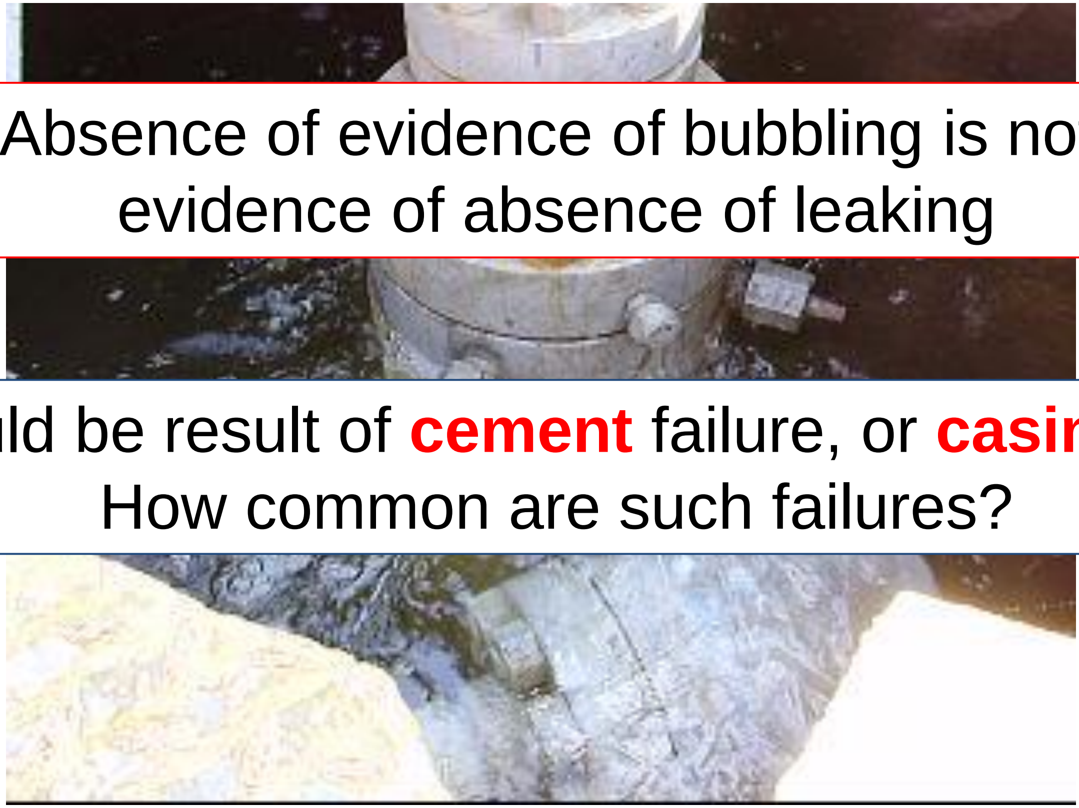


"There are at least three possible mechanisms for fluid migration into the shallow drinking-water aquifers that could help explain the increased methane concentrations we observed near gas wells…A second mechanism is leaky gas-well **casings**…Such leaks could occur at hundreds of meters underground, with methane passing laterally and vertically through fracture systems."

From Osborn et al. PNAS, 2011

What Is Concern About Cement/Casing Failure?

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".

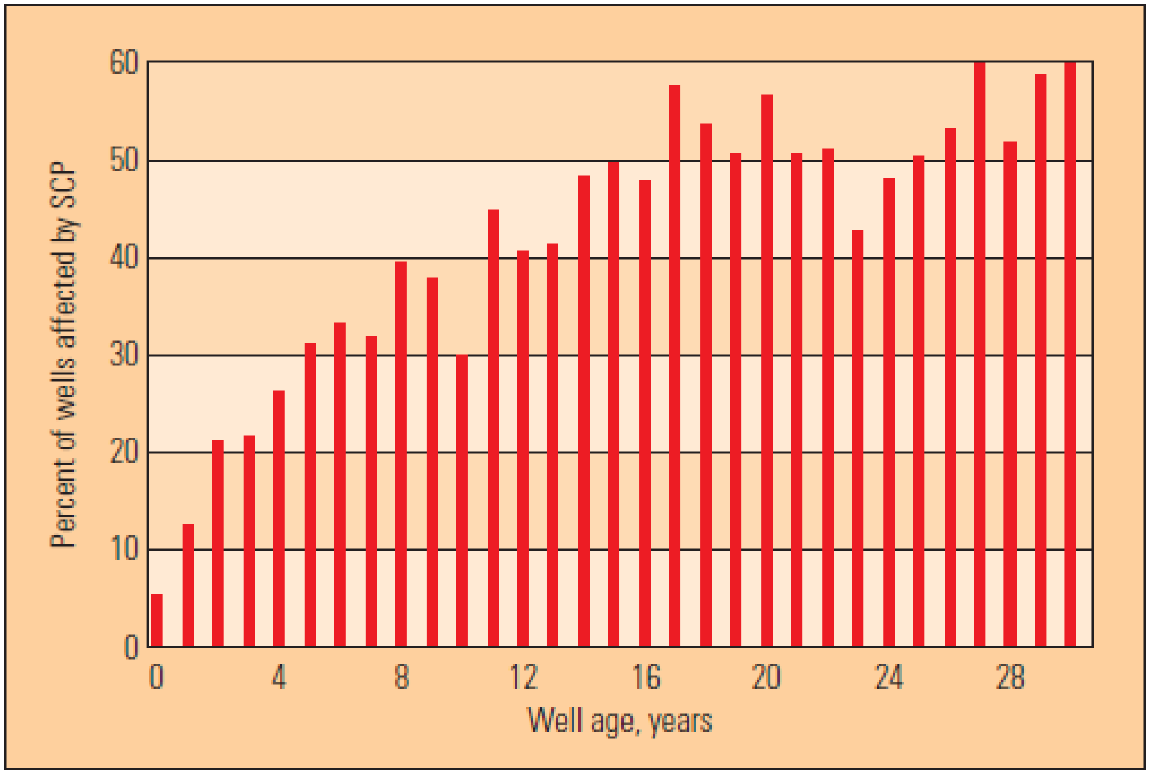


Absence of evidence of bubbling is not evidence of absence of leaking

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



^ 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.

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

Brufatto *et al.*, *Oilfield Review*, Schlumberger, Autumn, 2003

Industry-Reported Data On Loss of Wellbore Integrity: Onshore Wells

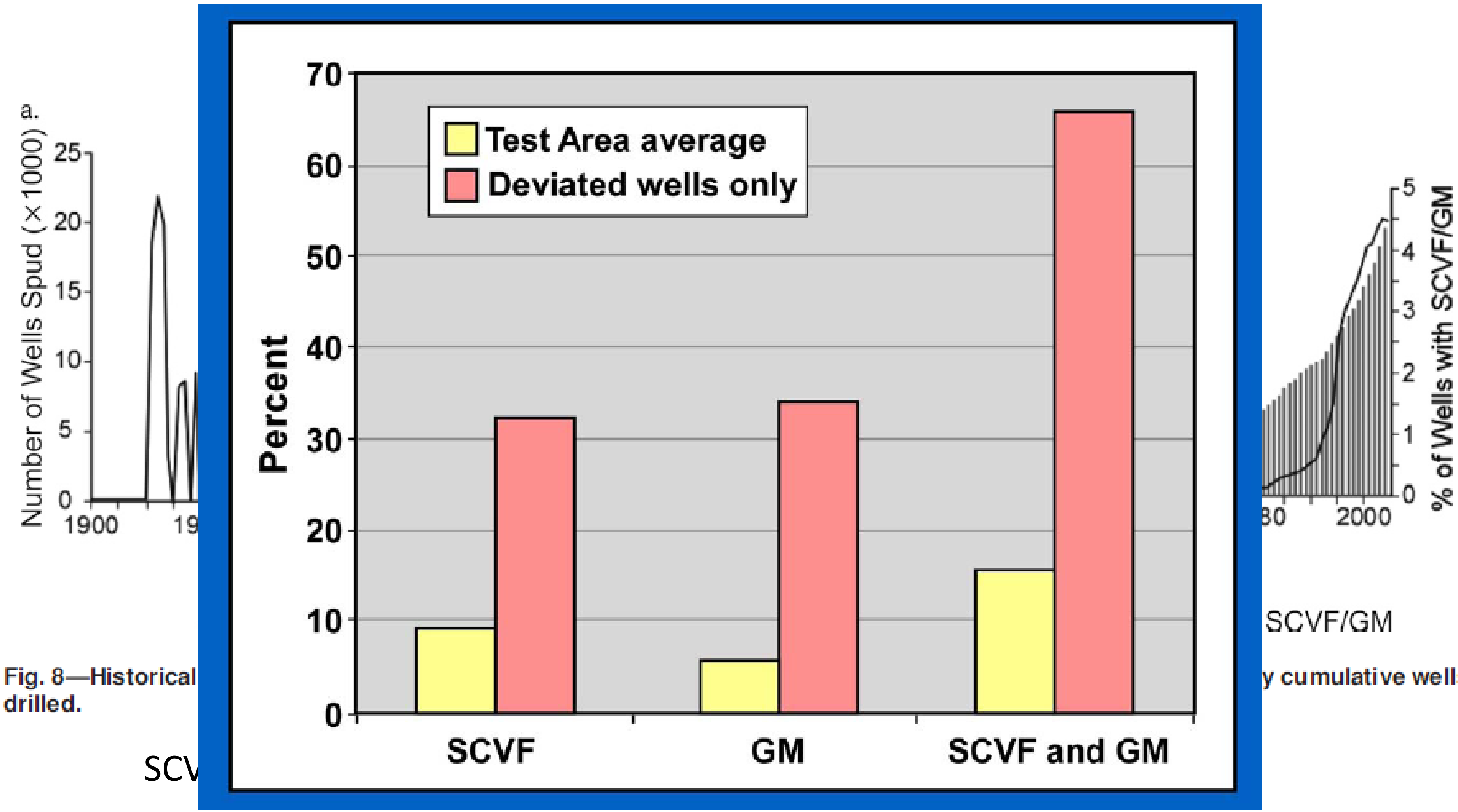


Fig. 8—Historical … y cumulative wells drilled.

SCV…

Watson and Bachu, SPE 106817, 2009.

Society of Petroleum Engineers
Webinar on Wellbore Integrity
Paul Hopman
March 27, 2013

Industry well integrity outlook

- Industry will drill more wells in next decade then 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

9

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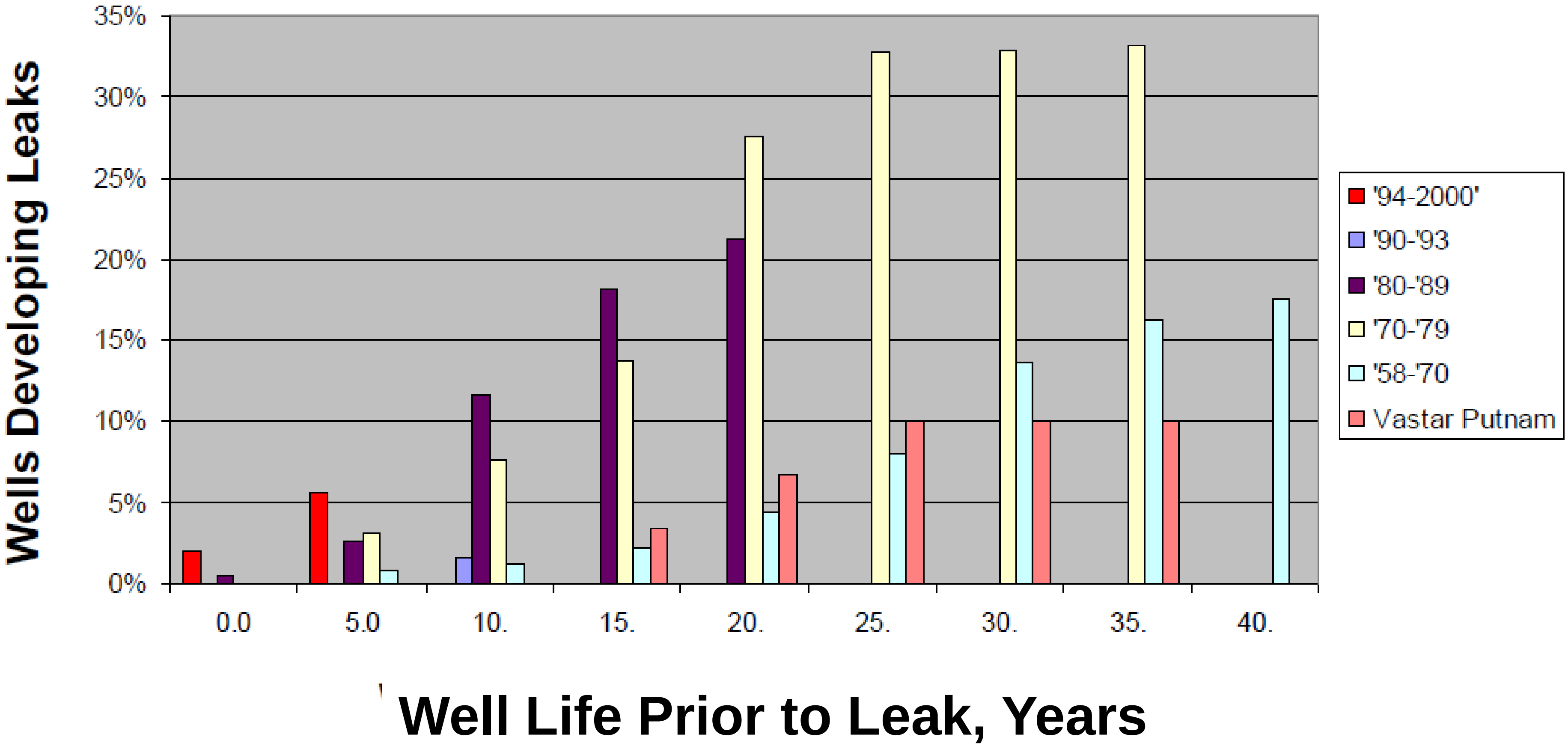
Leaky Well Industry Statistics



From George E King Consulting Inc.: http://gekengineering.com/id6.html

Columbus, Ohio • Aug 08, 2013
The Columbus Dispatch
Dispatch.com

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

*Ingraffea et al. Assessment and Risk Analysis of Casing and Cement Impairment in Oil and Gas Wells In Pennsylvania: 2000-2012. In review, March, 2014.

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.

PA DEP Chapter 78 Violation Codes Used in 1st Filter

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

(Source: PADEP (2013a))

Indicator Keywords and Descriptions Used in 2nd Filter

Indicator (#)	Description	Keywords/phrasing
Cement Squeeze (34)	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	“squeeze”, “squeeze*”, “eeze”, “perf and patch”, “perf”
Top Job (13)	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.	"top job”, “topped off”, “cement drop*”, “cement fall”, “cement not to surface"
Annular Gas (20)	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.	“LEL”, “comb*”, “annular gas”, “annular vent”
SCP (69)	Sustained Casing Pressure	“bubbling”, “bubbl*”,“bleed”, “bled down”
Other (9)	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.	“remediation”, “recement”, “cement fail*”, “casing fail*”, “casing patch”, “Improper casing”, “improper cement”, “gas migration”, “gas leak*”

** Indicates a wildcard search*

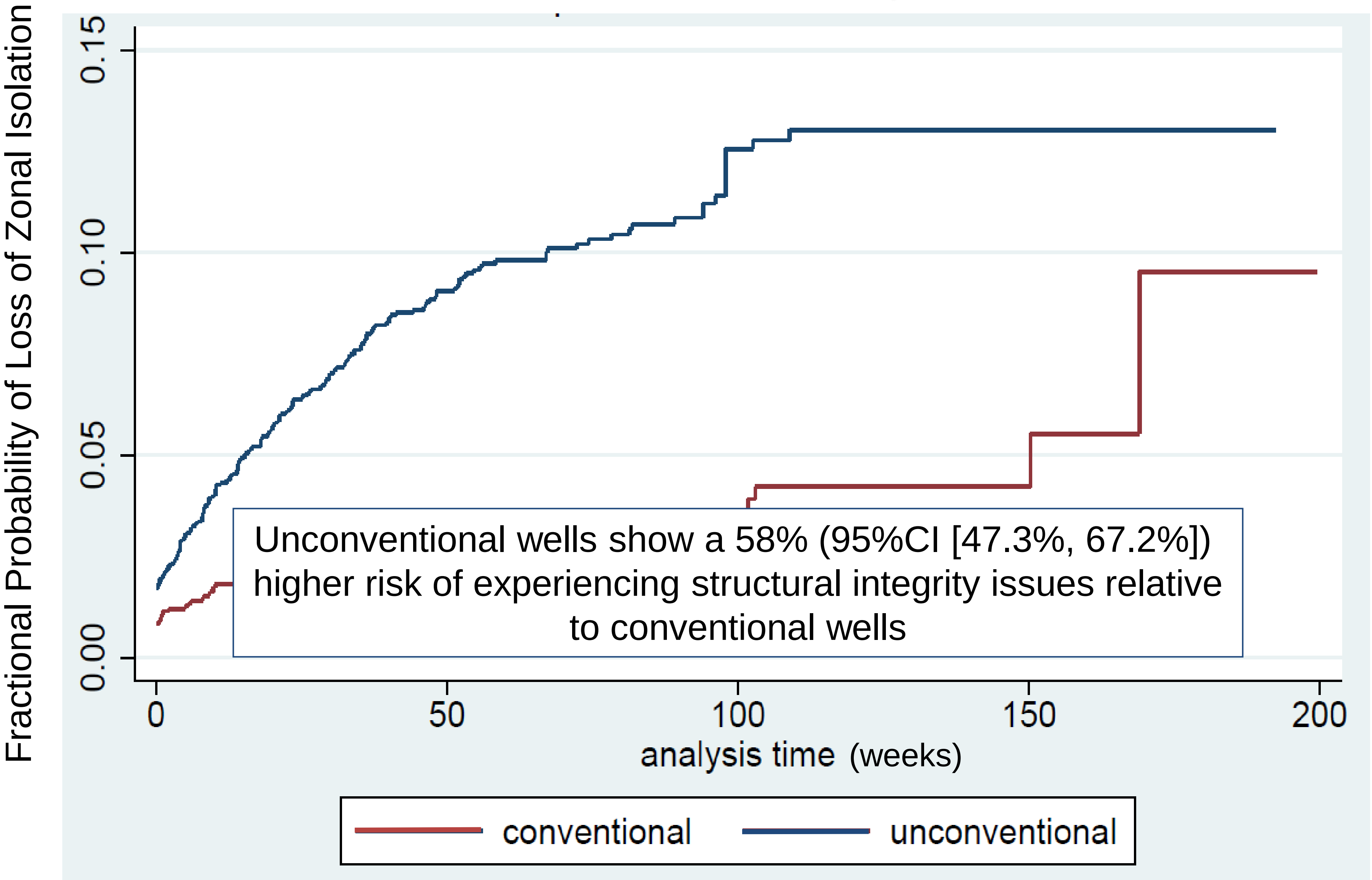
Wells With Indicators, Statewide

Spud Year	Conventional Wells			Unconventional Wells			Statewide Total		
	Indicator	Inspected	%	Indicator	Inspected	%	Indicator	Inspected	%
2000	5	1389	0.40%	0	0	0	5	1389	0.4%
2001	10	1827	0.50%	0	0	0	10	1827	0.5%
2002	10	1564	0.60%	0	1	0	10	1565	0.6%
2003	17	1940	0.90%	0	4	0	17	1944	0.9%
2004	14	2308	0.60%	0	2	0	14	2310	0.6%
2005	22	2949	0.70%	0	6	0	22	2955	0.7%
2006	42	3307	1.30%	3	23	13.0%	45	3330	1.4%
2007	28	3461	0.80%	2	83	2.40%	30	3544	0.8%
2008	34	3337	1.00%	15	304	4.90%	49	3641	1.3%
2009	17	1620	1.00%	56	749	7.50%	73	2369	3.1%
2010	16	1345	1.20%	148	1532	9.70%	164	2877	5.7%
2011	48	1055	4.50%	107	1862	5.70%	155	2917	5.3%
2012	17	813	2.10%	24	1197	2.00%	41	2010	2.0%
SUM	**280**	**26915**	**1.0%**	**355**	**5763**	**6.2%**	**635**	**32678**	**1.9%**

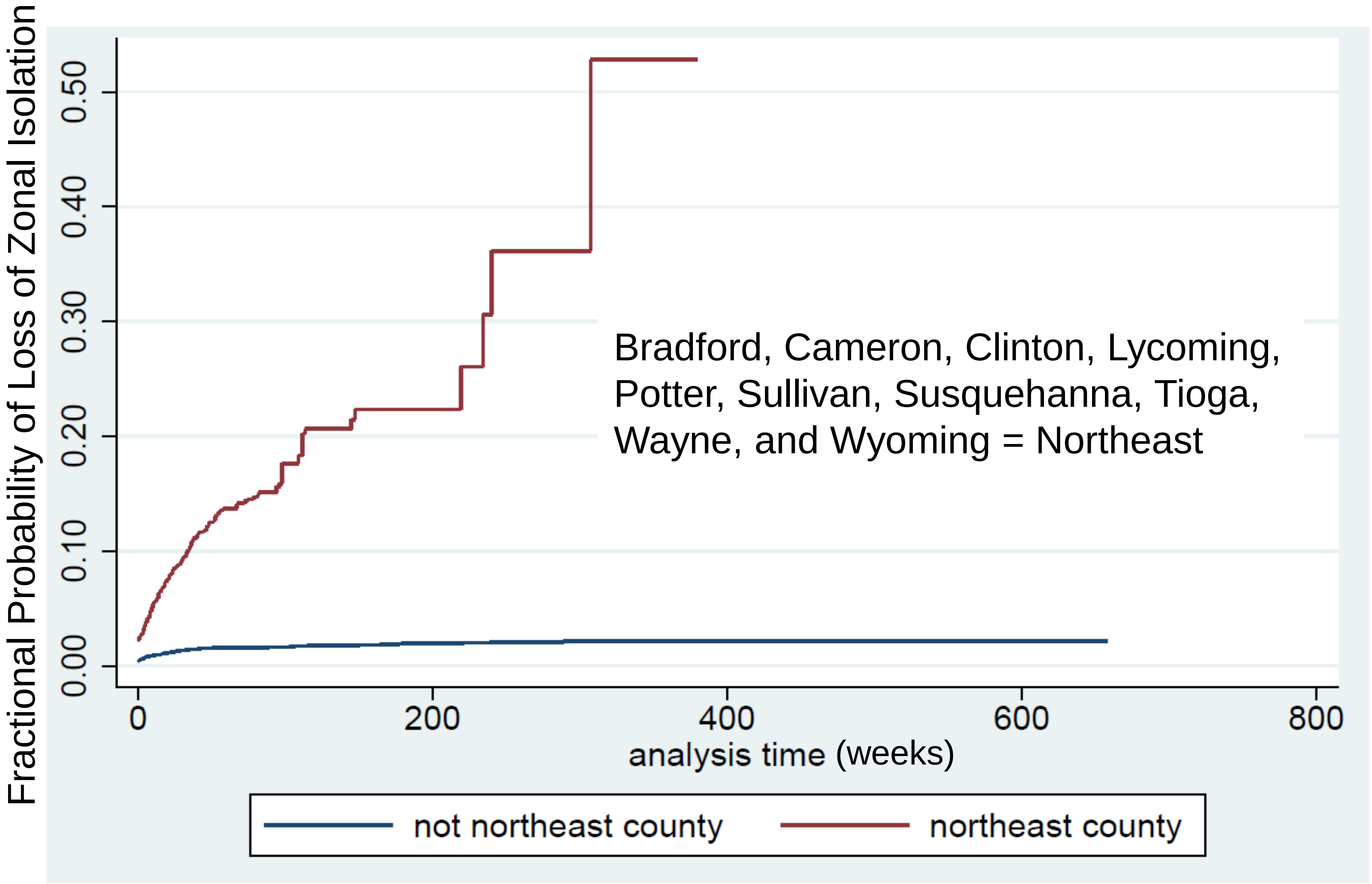
Well Failure Rate Analysis

- **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.**

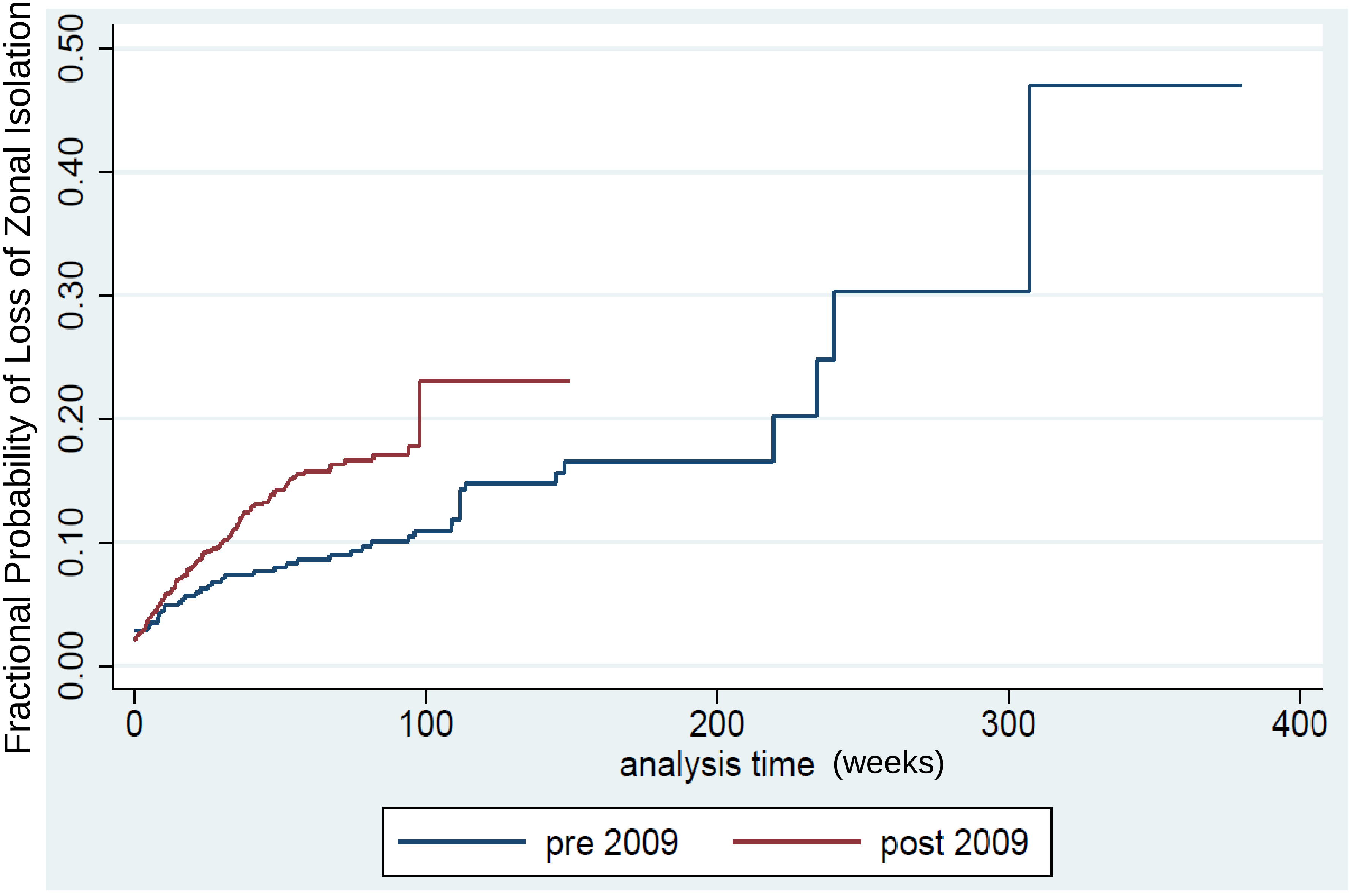
Hazard Prediction for Conventional and Unconventional Wells: Statewide, Post-2009 Data



Hazard Prediction for Northeast and Non-Northeast Counties: All Wells



Hazard Prediction for Northeast PA Counties, Pre- and Post-2009 Spuds



Observations and Implications

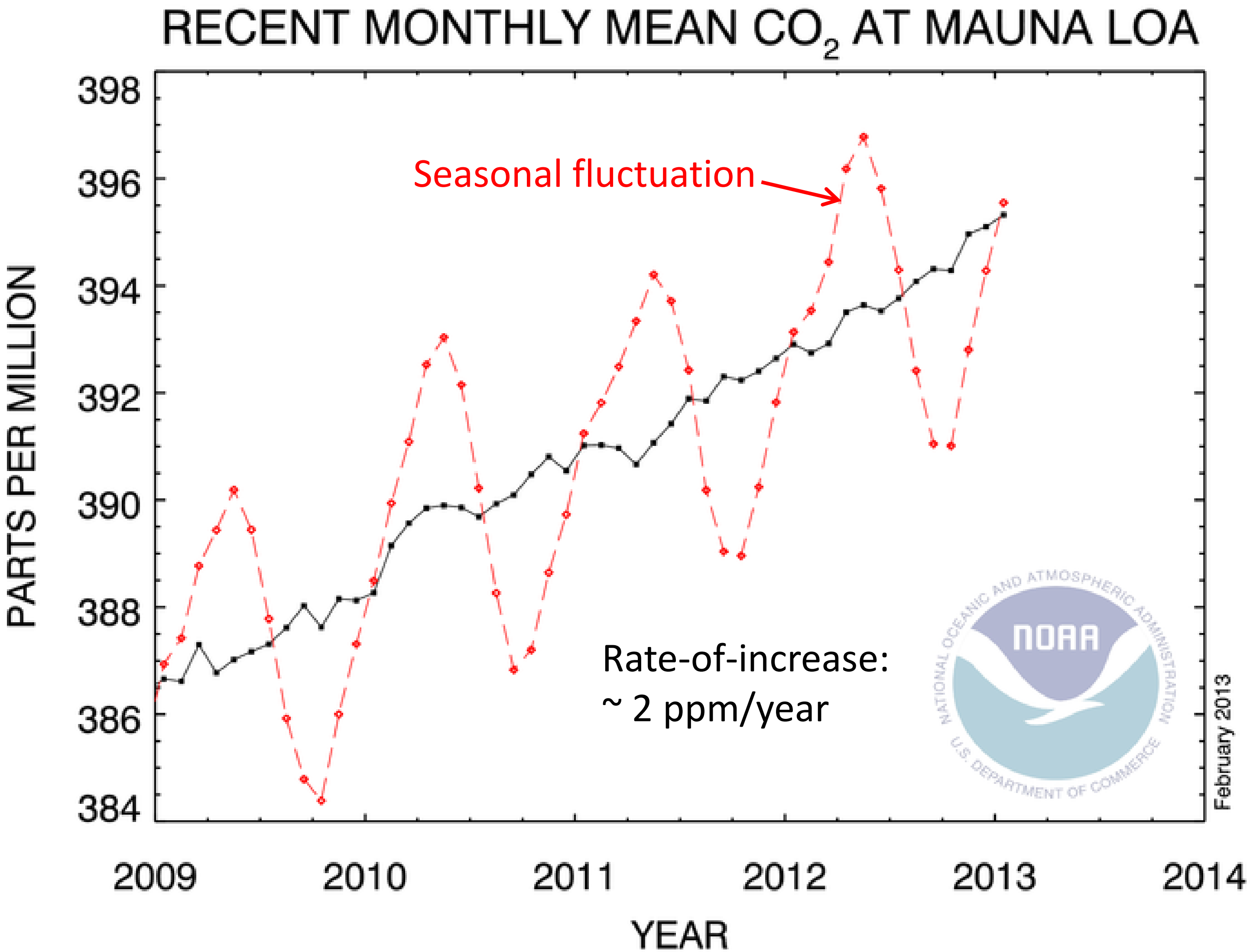
- Cement/casing failure is chronic and well-known mode of loss of wellbore integrity.
- Thorough analysis of well integrity data in "modern" shale wells under "tough" regulations indicates significant failure rate continues.
- Support for hypothesis that methane migration incidents are resulting from "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.

Why NOT More Shale Gas/NGL/Oil?

"Methane is a clean fossil fuel. Methane is a cleaner fossil fuel. Methane is the bridge fuel to a green renewable energy future."

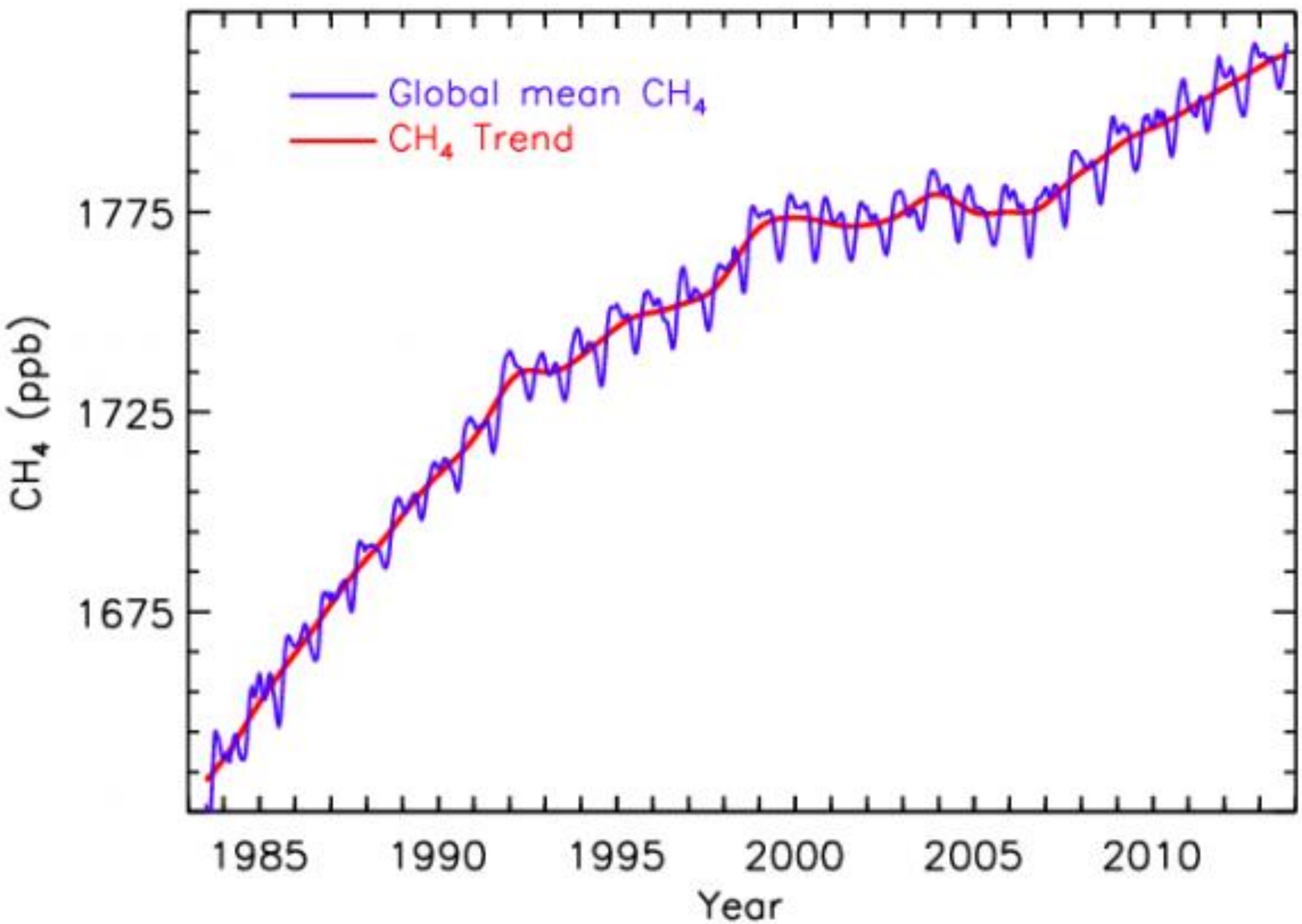
Part 2 of My Talk: Methane is not a clean fossil fuel: no such thing. Methane is not a cleaner fossil fuel: it is the dirtiest from a climate change perspective. It is not a bridge: it is a gangplank.

CO_2 Concentration in the Atmosphere



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?

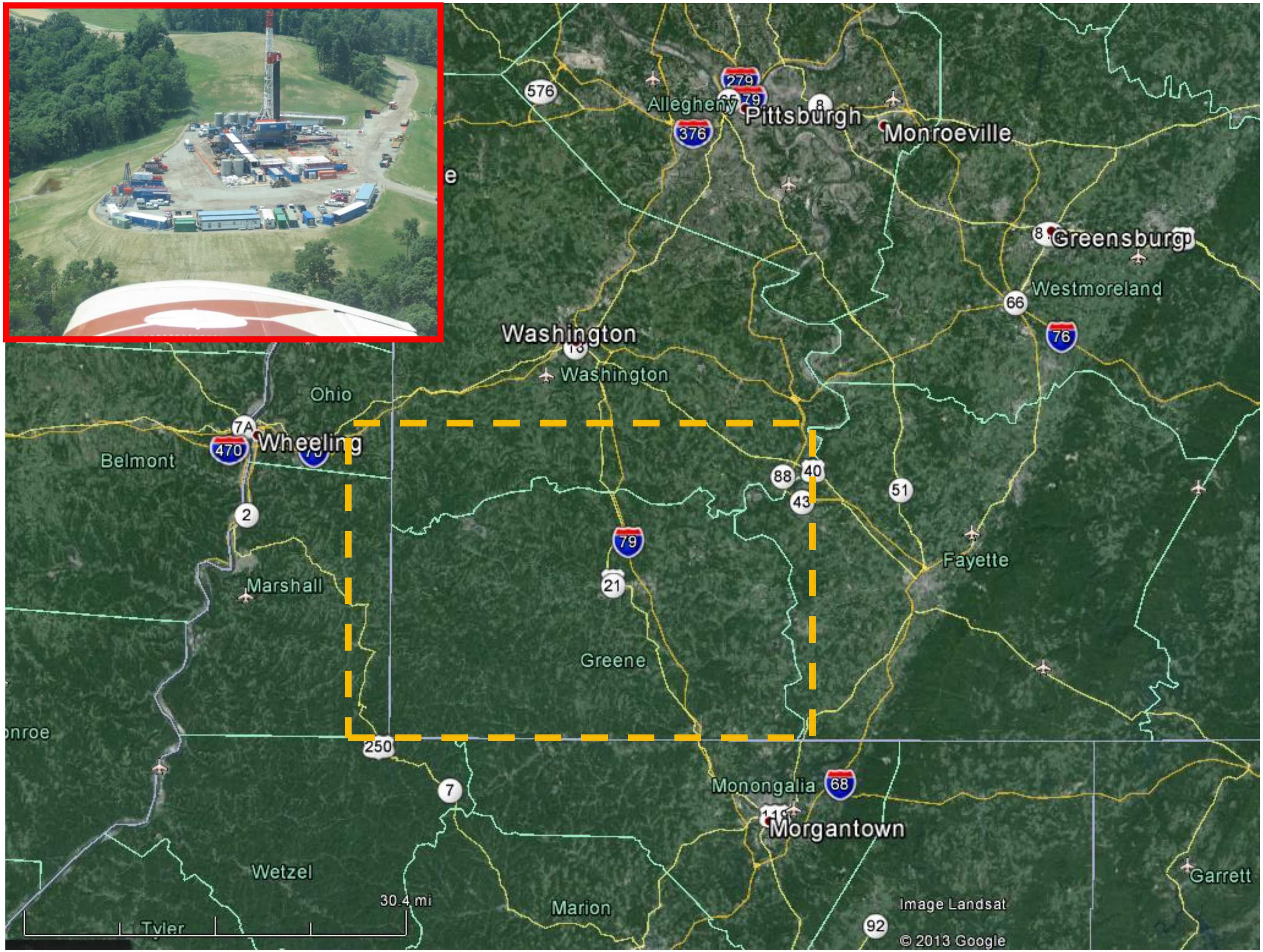
Upstream/Midstream Methane Emission *Measurements* are Coming in Very High Relative to EPA *Estimate* of 1.8%

Uinta Basin, Utah:
Up to 9% of total production
Karion et al. *Geophys. Res. Lett.* **40**, 4393 (2013).

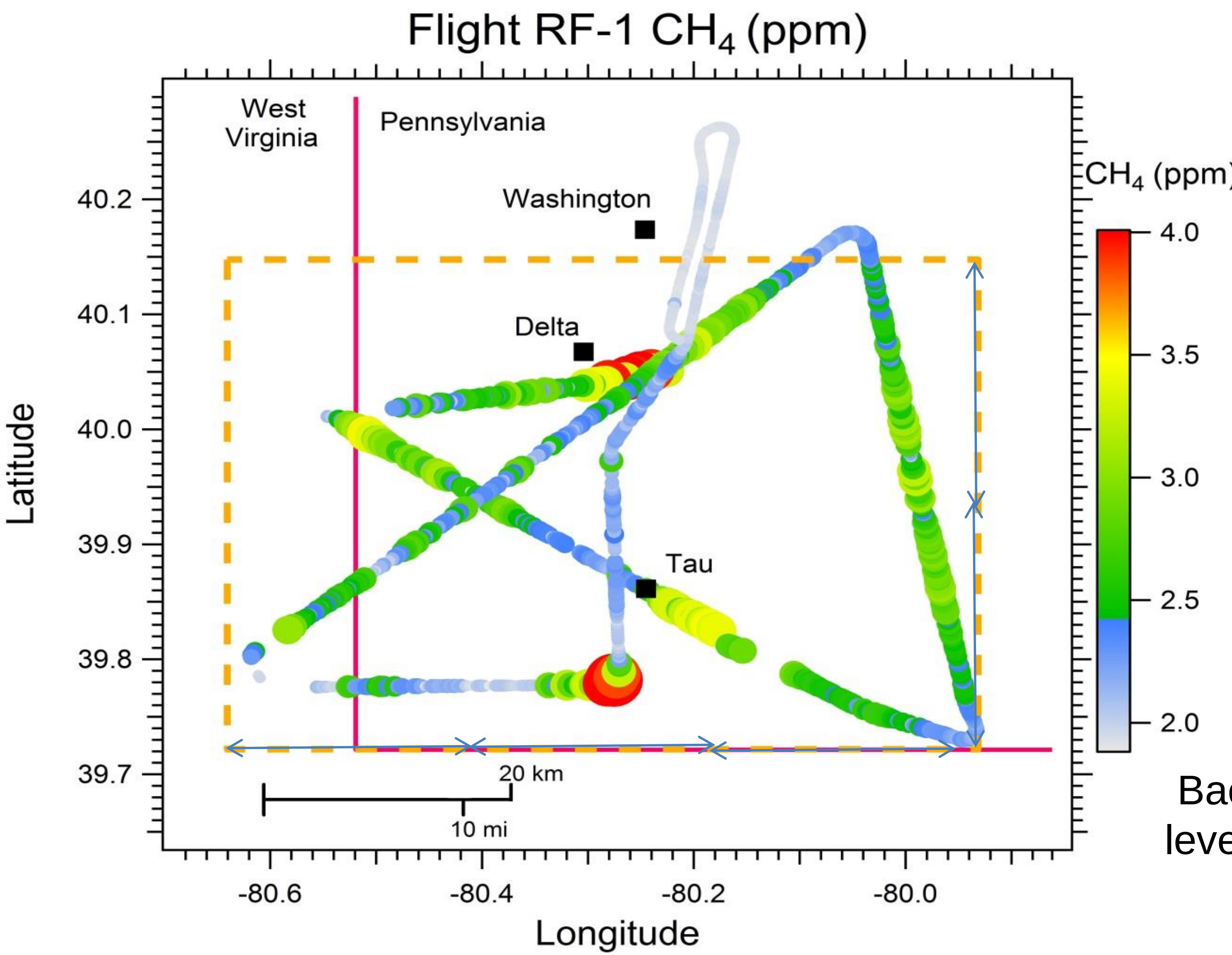
Denver–Julesburg Basin, Colorado:
2.3% to 7% of total production
Pétron, G. *et al*. J. Geophys. Res. **117**, 4304 (2012)

Los Angeles Basin, California
~ 17% of total production but includes natural seeps
Pistil *et al.*, *J. Geophysics. Res.* **118**, 4974 (2013).

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



Background level, 1.9 ppm

Caulton et al. Toward a Better Understanding and Quantification of Methane Emissions from Shale Gas Development. To Appear, PNAS, 2014.

Pad DELTA Drilling on Air

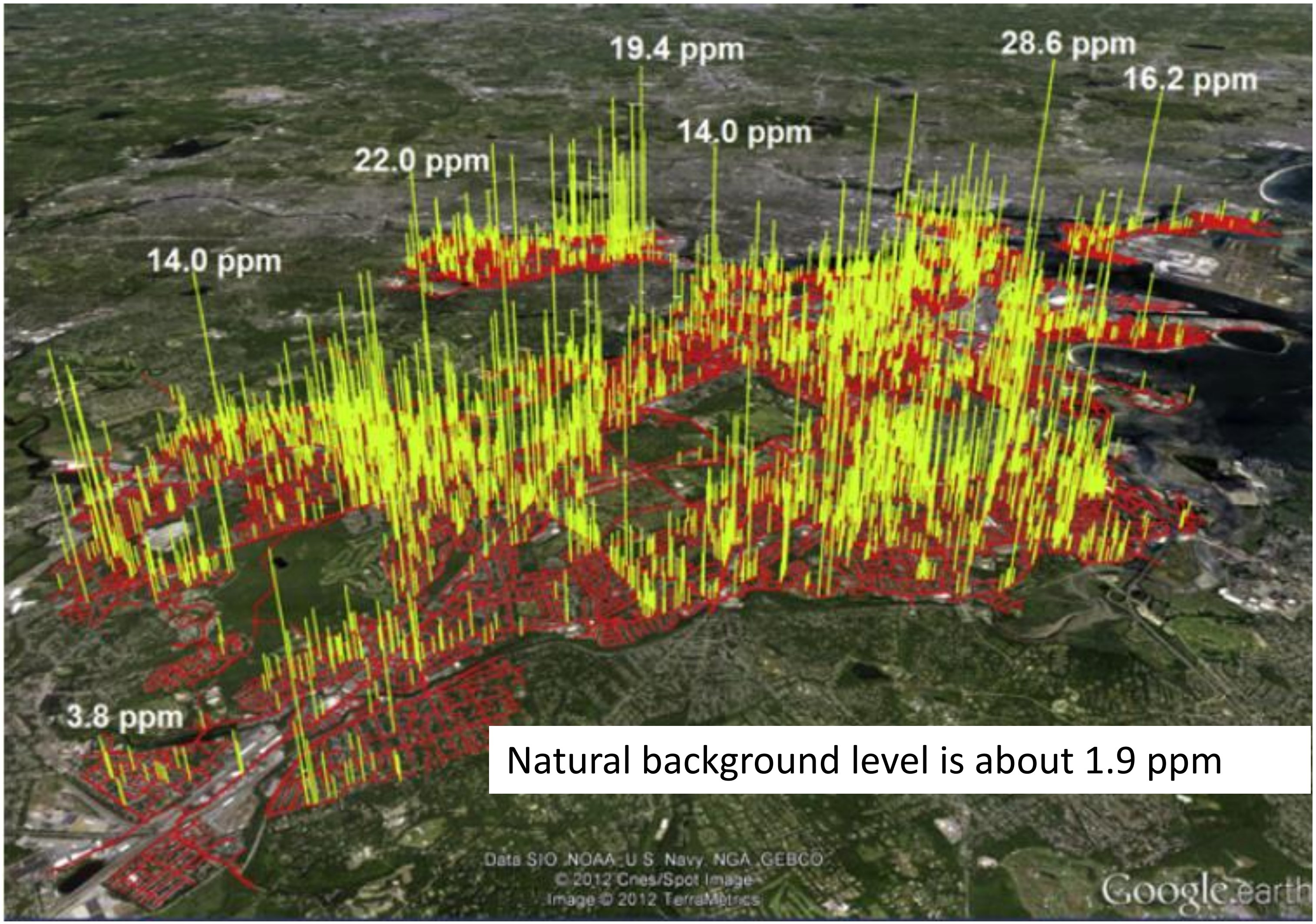
a. Drill rig
b. Unlit but venting flare stack
c. Air compressors
d. Main high-pressure air line
e. Flow line
f. Separator unit
g. Water tanks

Natural Gas Portion of the Top-Down Flux as a Percentage of Natural Gas Production

	18 hour Estimate		5-6 hour Estimate	
Top-Down Flux	3.1 g $CH_4 s^{-1} km^{-2}$		10.3 g $CH_4 s^{-1} km^{-2}$	
CH_4 from Nat. Gas	22%	62%	22%	62%
Nat. Gas Prod. Rate	15.9 g $CH_4 s^{-1} km^{-2}$		50.1 g $CH_4 s^{-1} km^{-2}$	
Nat. Gas Flux/ Prod. Rate	**4.3%**	**12.1%**	**4.5%**	**12.7%**

Caulton et al. Toward a Better Understanding and Quantification of Methane Emissions from Shale Gas Development. To Appear, PNAS, 2014.

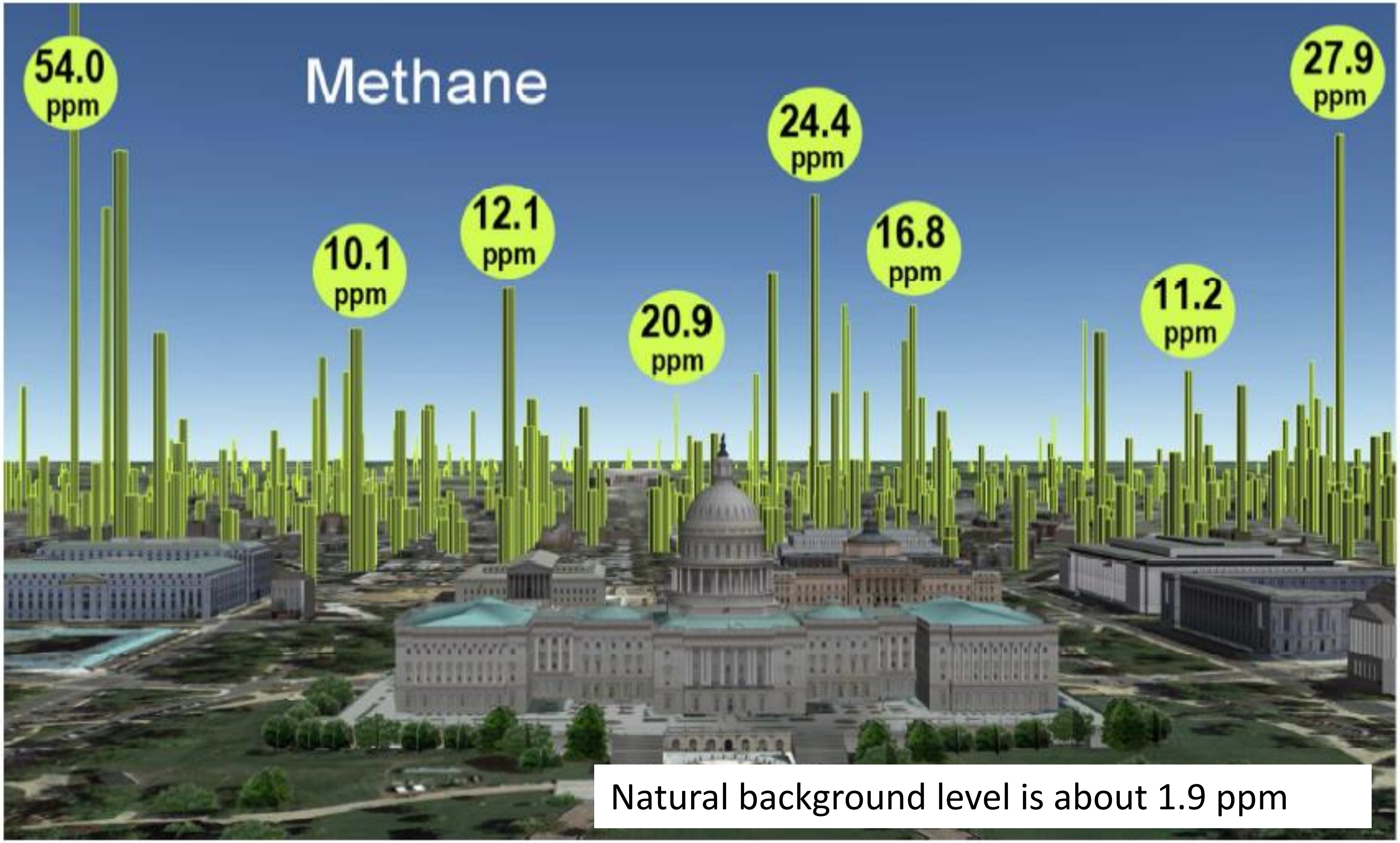
Downstream Methane Leakage from Aging Urban Distribution Pipelines: Boston MA



Natural background level is about 1.9 ppm

N.G. Phillips et al. / Environmental Pollution 173 (2013) 1–4

Downstream Methane Leakage from Aging Urban Distribution Pipelines: DC



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

Miller et al. Quantification of US methane emissions, including large fossil fuel sources over the South-Central Region. PNAS, November, 2013

"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 CH_4 emission factors for fossil fuel extraction and processing by 25–30% (for 1990–2011), **but we find that CH_4 data from across North America instead indicate the need for a larger adjustment of the opposite sign."**

Brandt et al. Methane Leaks from North American Natural Gas Systems, SCIENCE, February 13, 2014

"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:

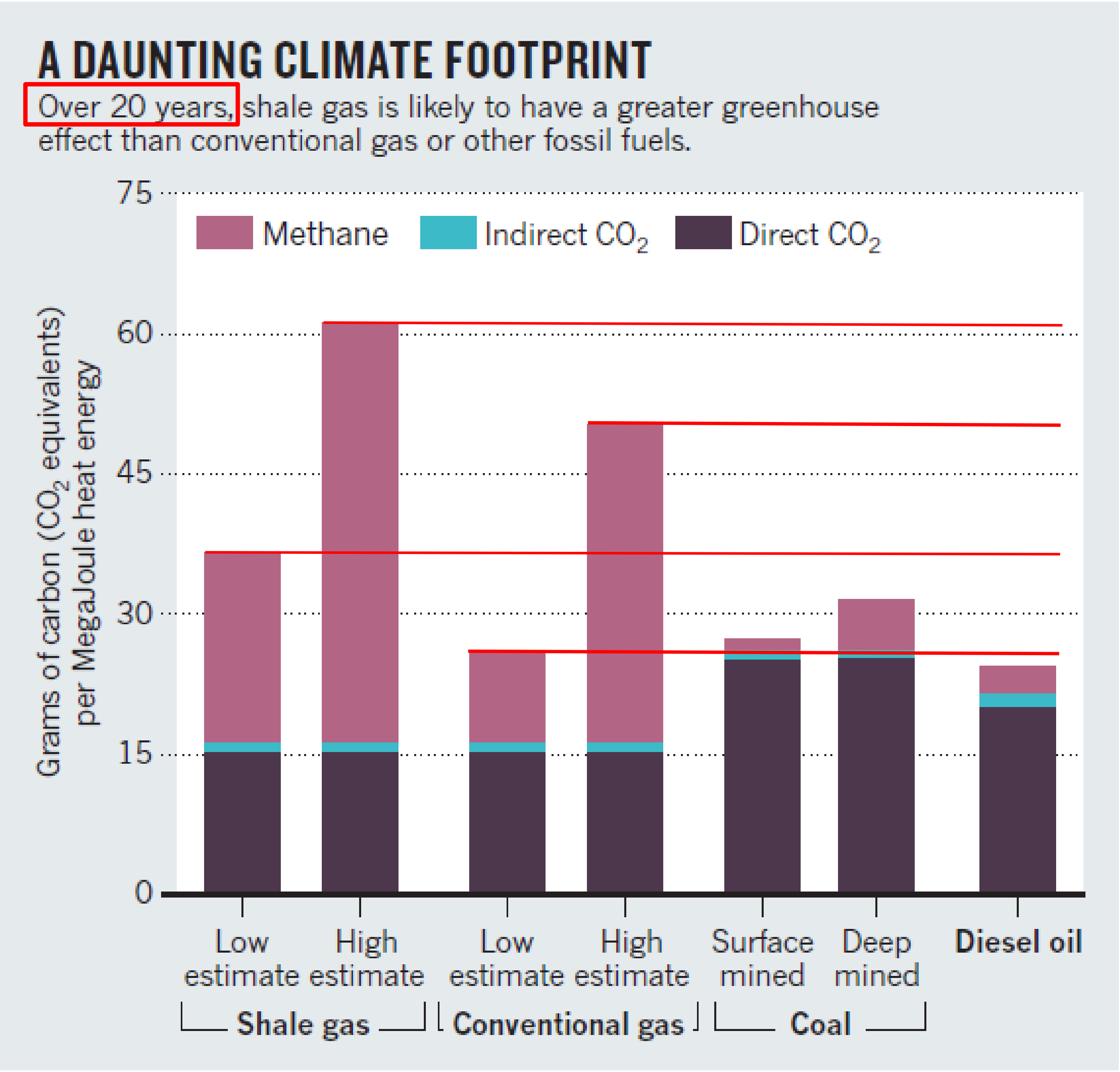
- A Technology Question: How much methane is being emitted by oil/gas operations?
- **A Science Question: What is impact on climate change of methane emissions?**
- A Policy Question: Over what period of time should we measure that impact?

Methane Is a Much More Potent Greenhouse Gas Than Carbon Dioxide

- Up to 34 times more potent over 100 years*
- <u>Up to 86</u> times more potent over <u>20 years*</u>
- Therefore, even small leakage rates important:

  Over 20 years, each <u>1%</u> lifetime production leakage from a well produces nearly the same climate impact as burning the methane <u>twice</u>.

*IPCC AR5, October, 2013



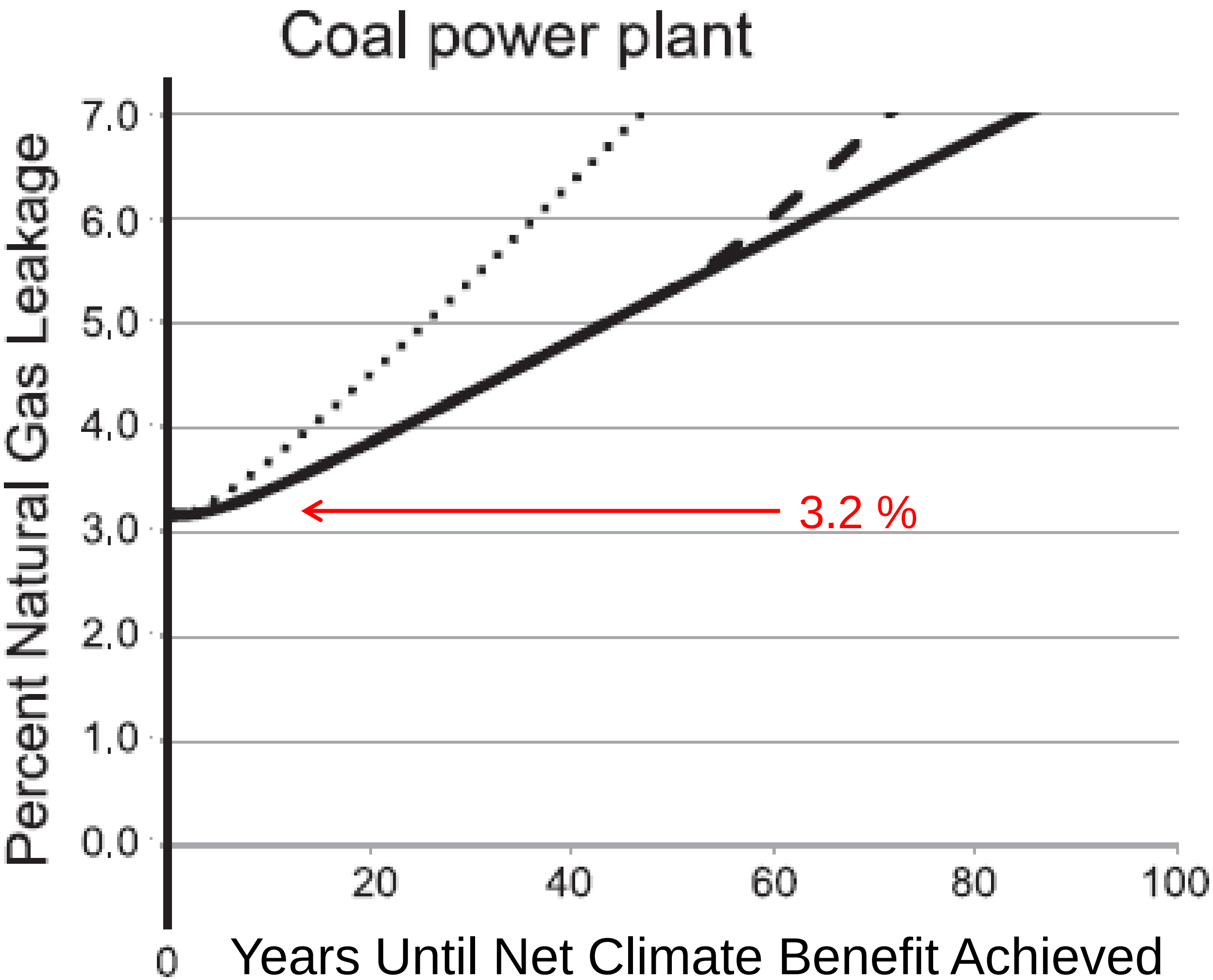
Howarth, Ingraffea, NATURE, 477, 2011

That 3.2% Number

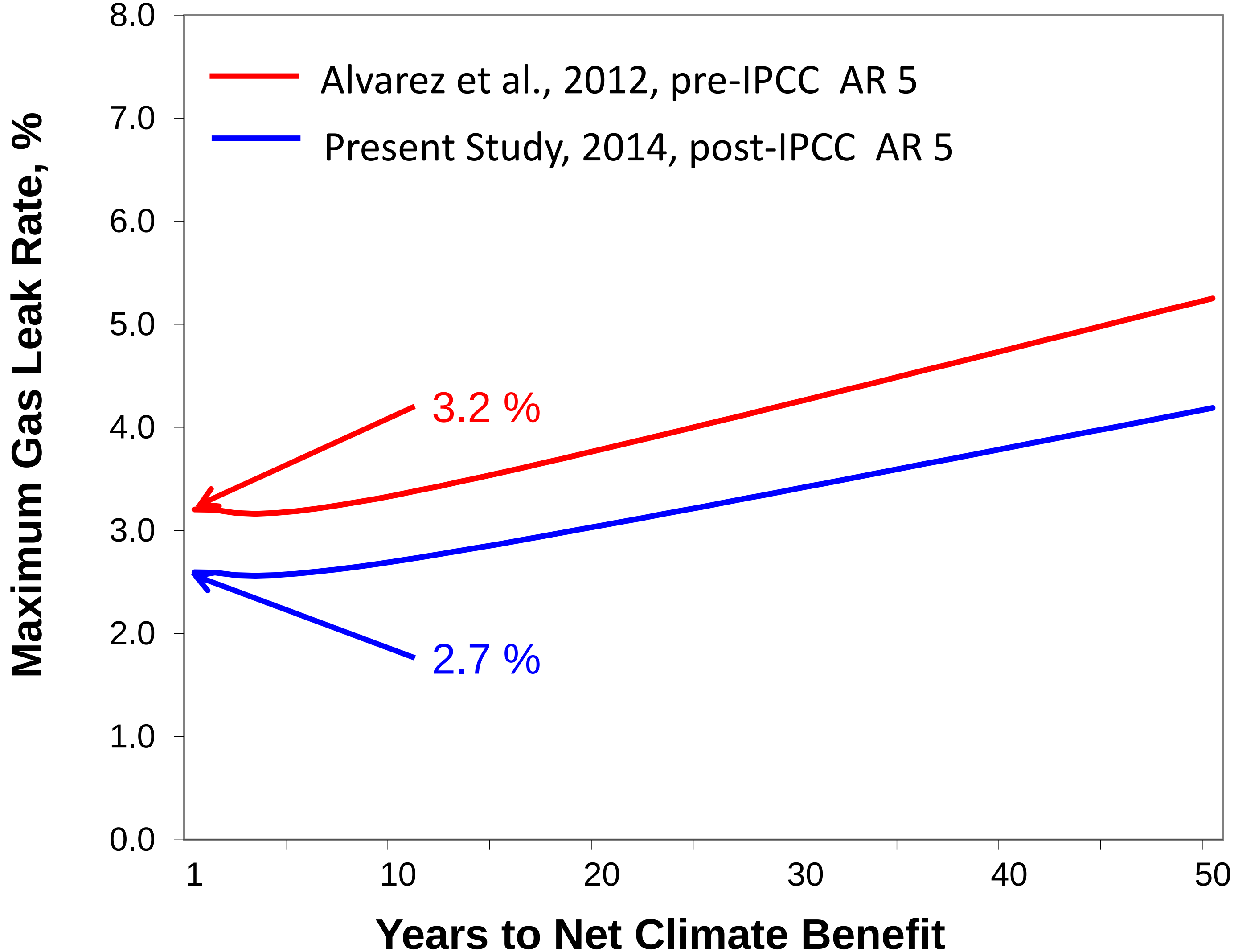
Origen: A paper by, Alvarez *et al*., “Greater focus needed on methane leakage from natural gas infrastructure”, PNAS, 2012.

Claims 3.2% to be the immediate, average break-even leak rate for climate benefit of methane over coal for electricity generation

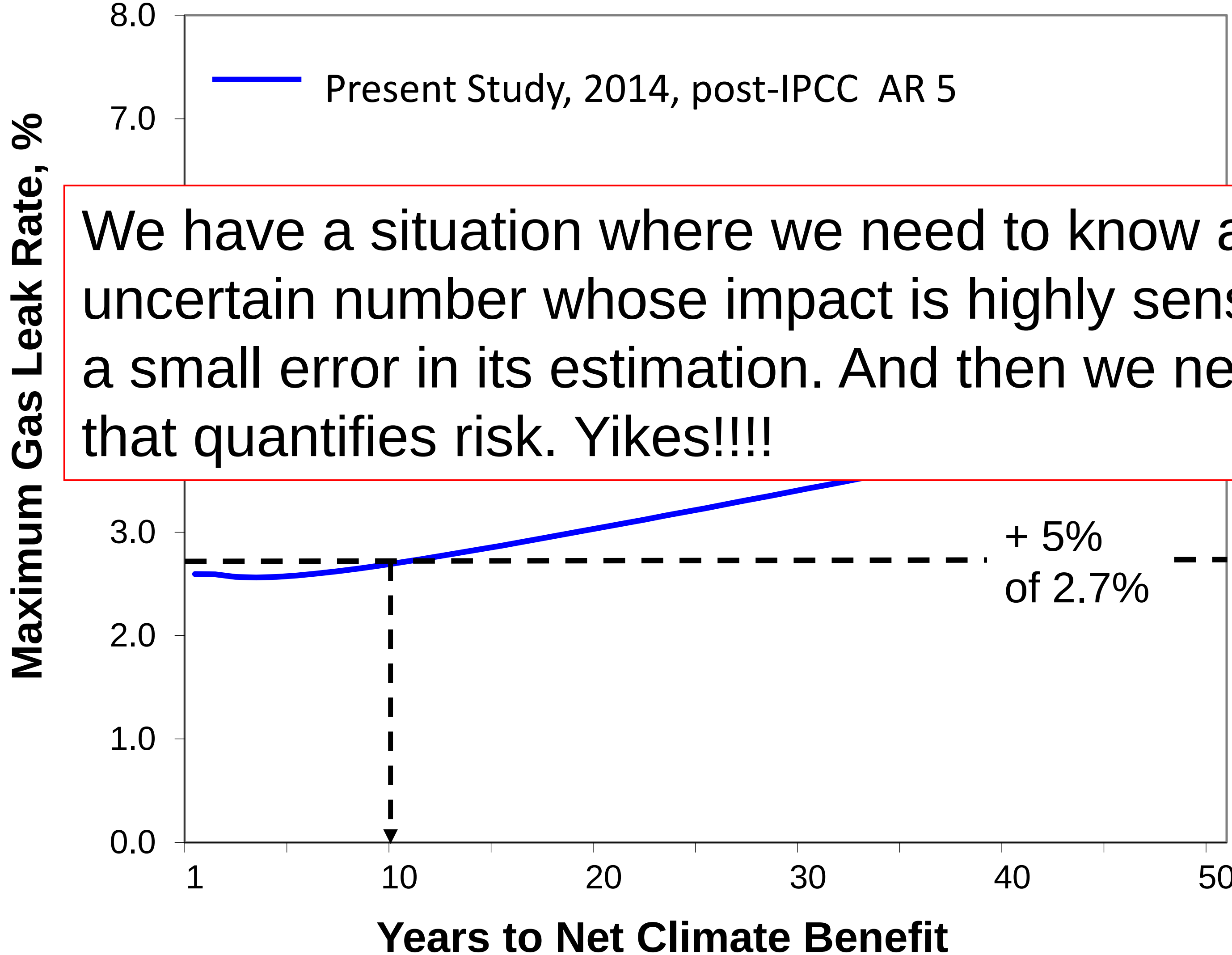
Methane a Winner for Electricity Generation, If….



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



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!!!!

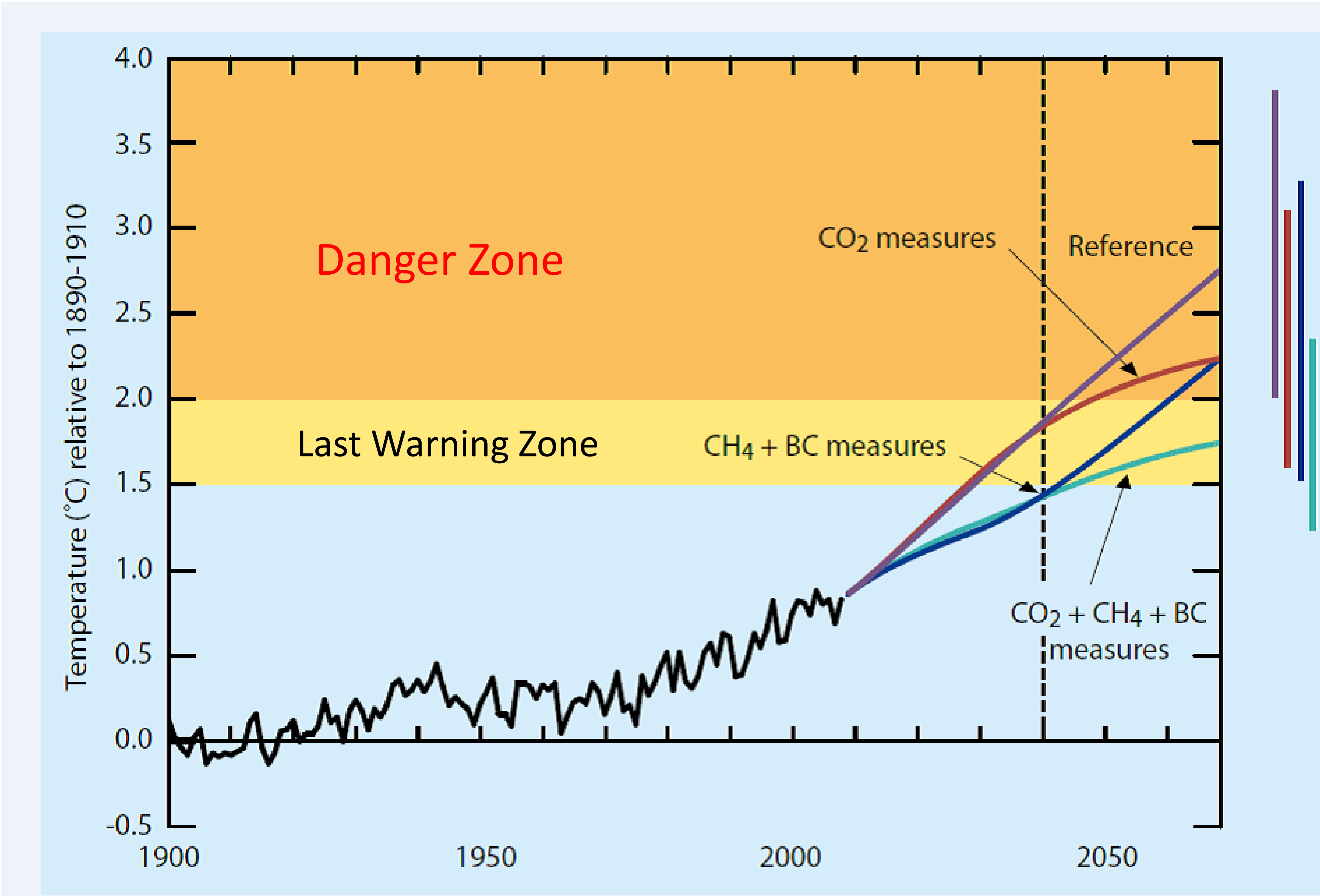
Again: Brandt et al. Methane Leaks from North American Natural Gas Systems, SCIENCE, February 13, 2014

"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.

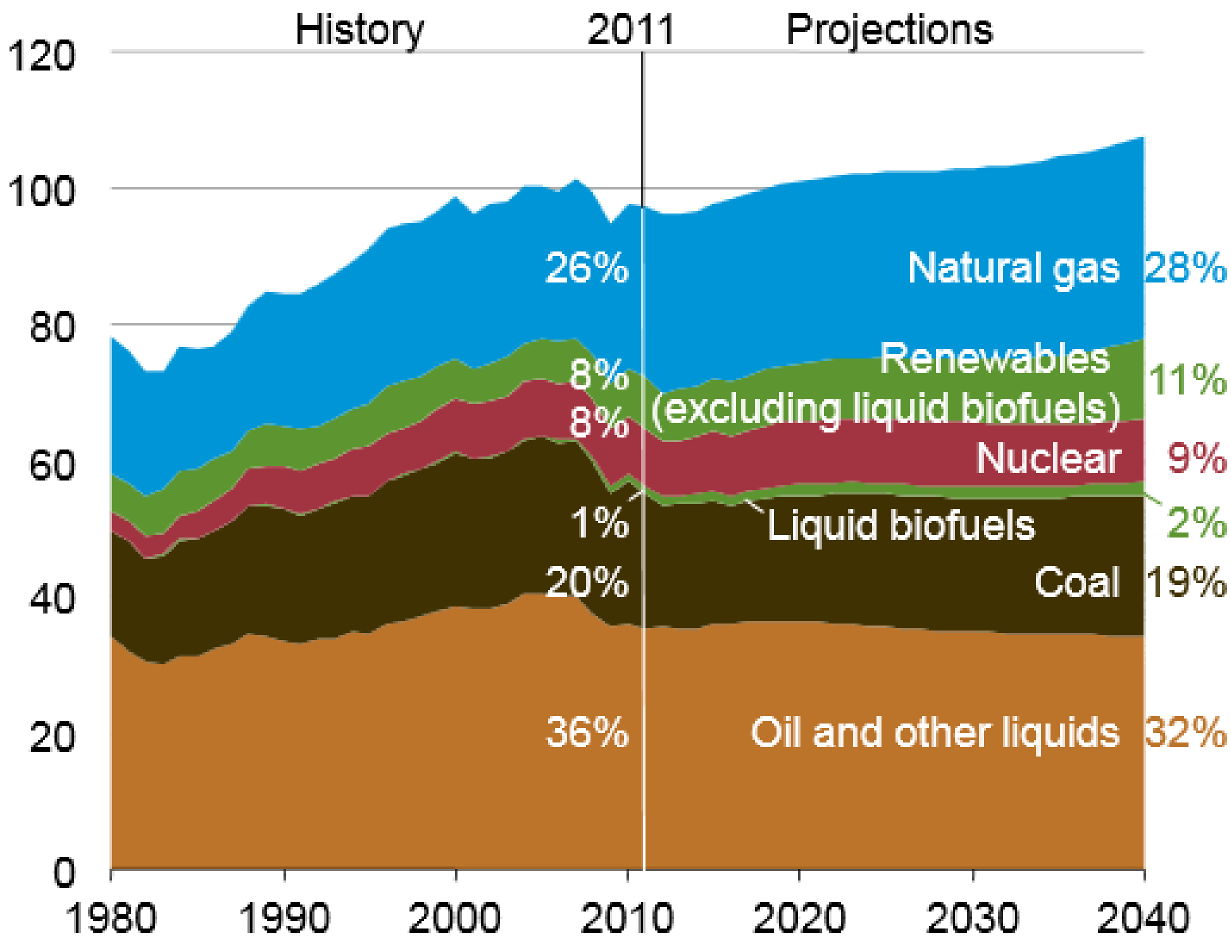
Why Is Controlling Methane (CH_4) Emission So Important?



Source: Shindell et al.(2012). Simultaneously mitigating near-term climate change and improving human health and food security. *Science 335: 183-189.*

Here is the U.S. Energy Information Agency Forecast

Figure 7. U.S. primary energy consumption by fuel, 1980-2040 (quadrillion Btu per year)



Fossil Fuel Divestment Statement

October 3, 2013 | Cambridge, Mass.

“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