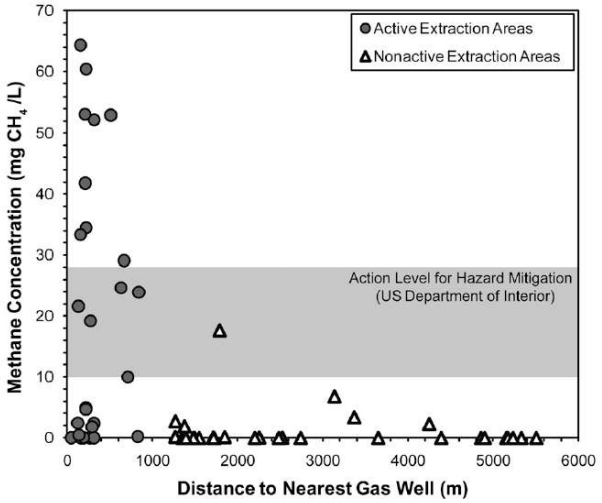
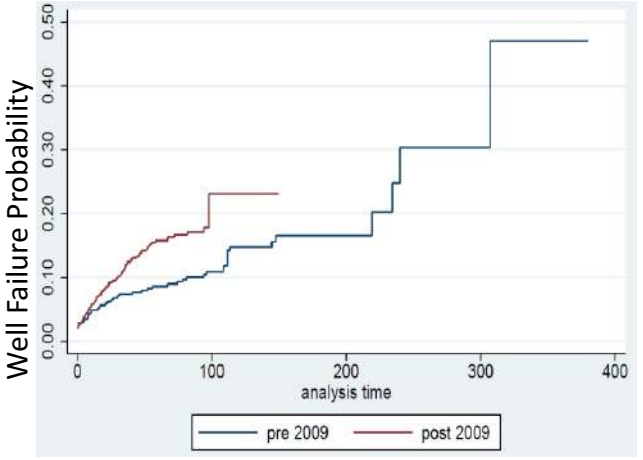




Risk of Cement/Casing Failure: Leaking Wells

A. R. Ingraffea, Ph.D., P.E.
Dwight C. Baum Professor of Engineering
Cornell University
President: Physicians, Scientists, and Engineers for Healthy Energy, Inc.

Presentation to the Maryland Marcellus Shale Advisory Commission
***February* 10, 2014**

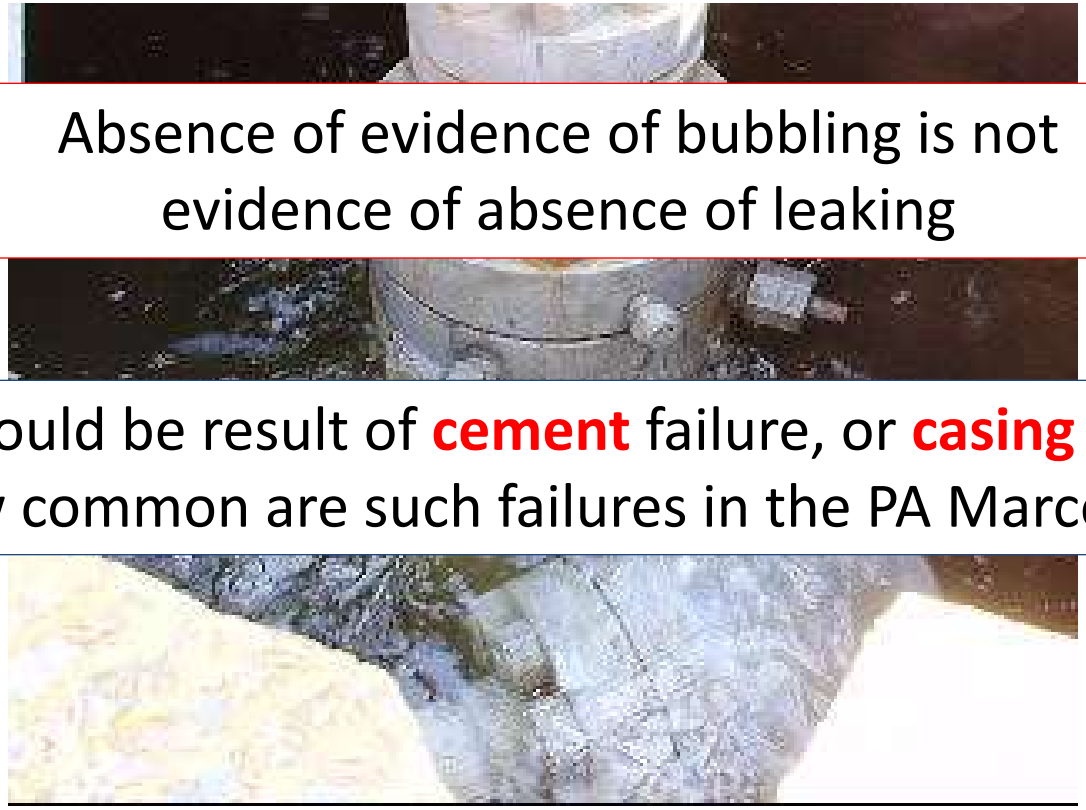
Words and Phrases that Describe "Leaking Wells"

- Loss of structural integrity
- Loss of wellbore integrity
- Loss of zonal isolation
- Barrier failure
- Sustained casing pressure (SCP)
- Sustained annular flow (SAF)
- Sustained casing vent flow (SCVF)
- Gas migration (GM)

What Is Concern About Cement/Casing Failure?

- Cement/Casing failure can cause a gas/oil well to "leak"

- A leaking gas/oil well may cause contamination of underground source of drinking water (USDW) and/or methane emissions to the atmosphere

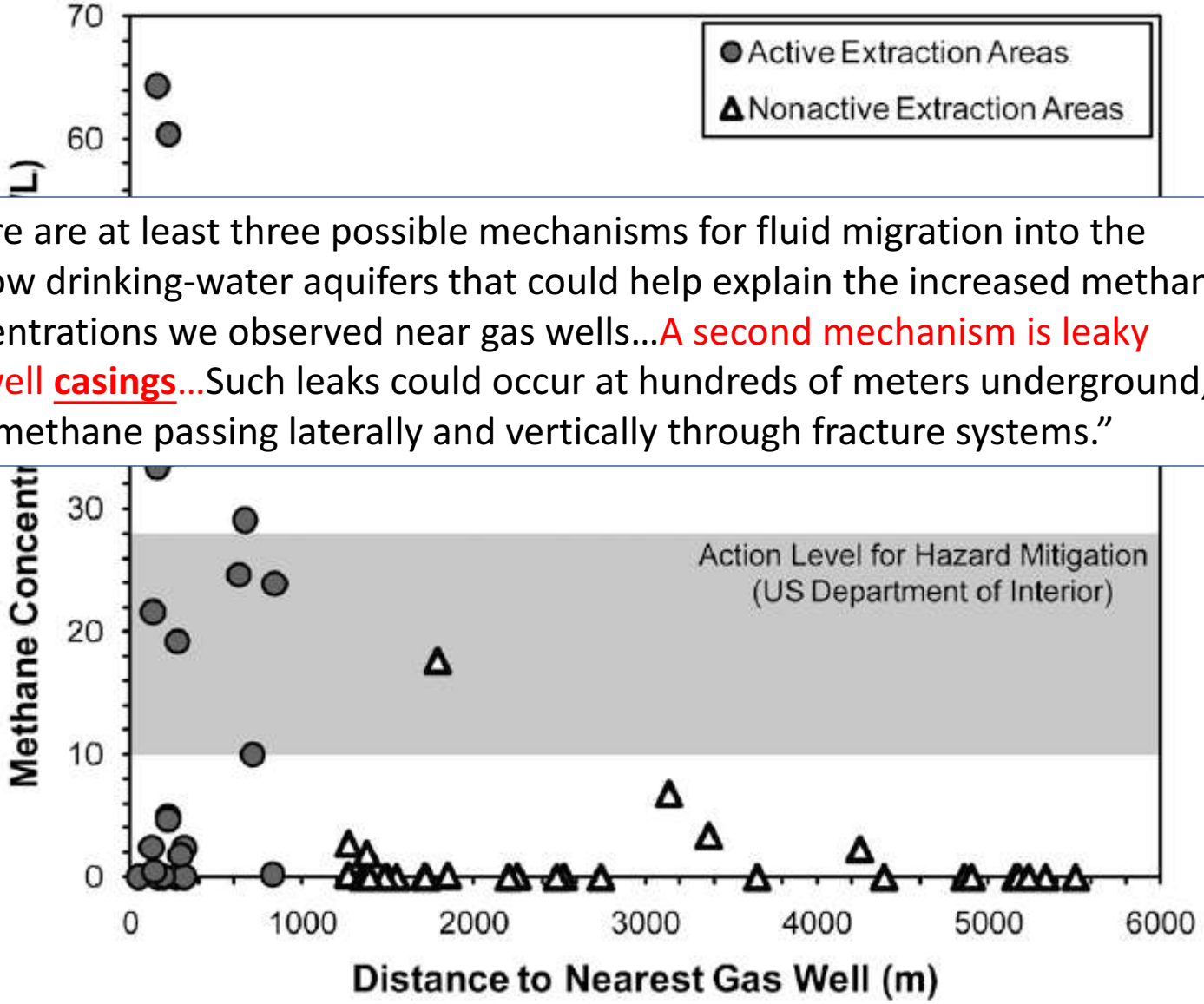


Absence of evidence of bubbling is not evidence of absence of leaking

This could be result of **cement** failure, or **casing** failure.
How common are such failures in the PA Marcellus?

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."



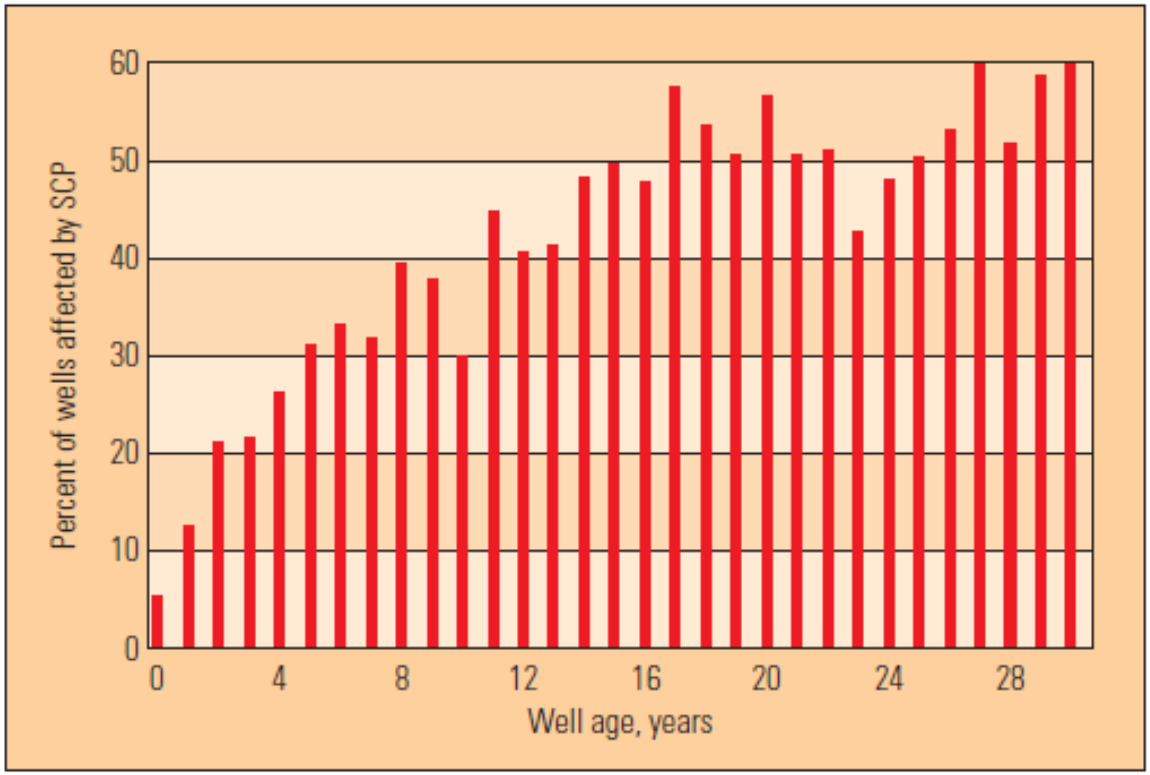
From Osborn et al. PNAS, 2011

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

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



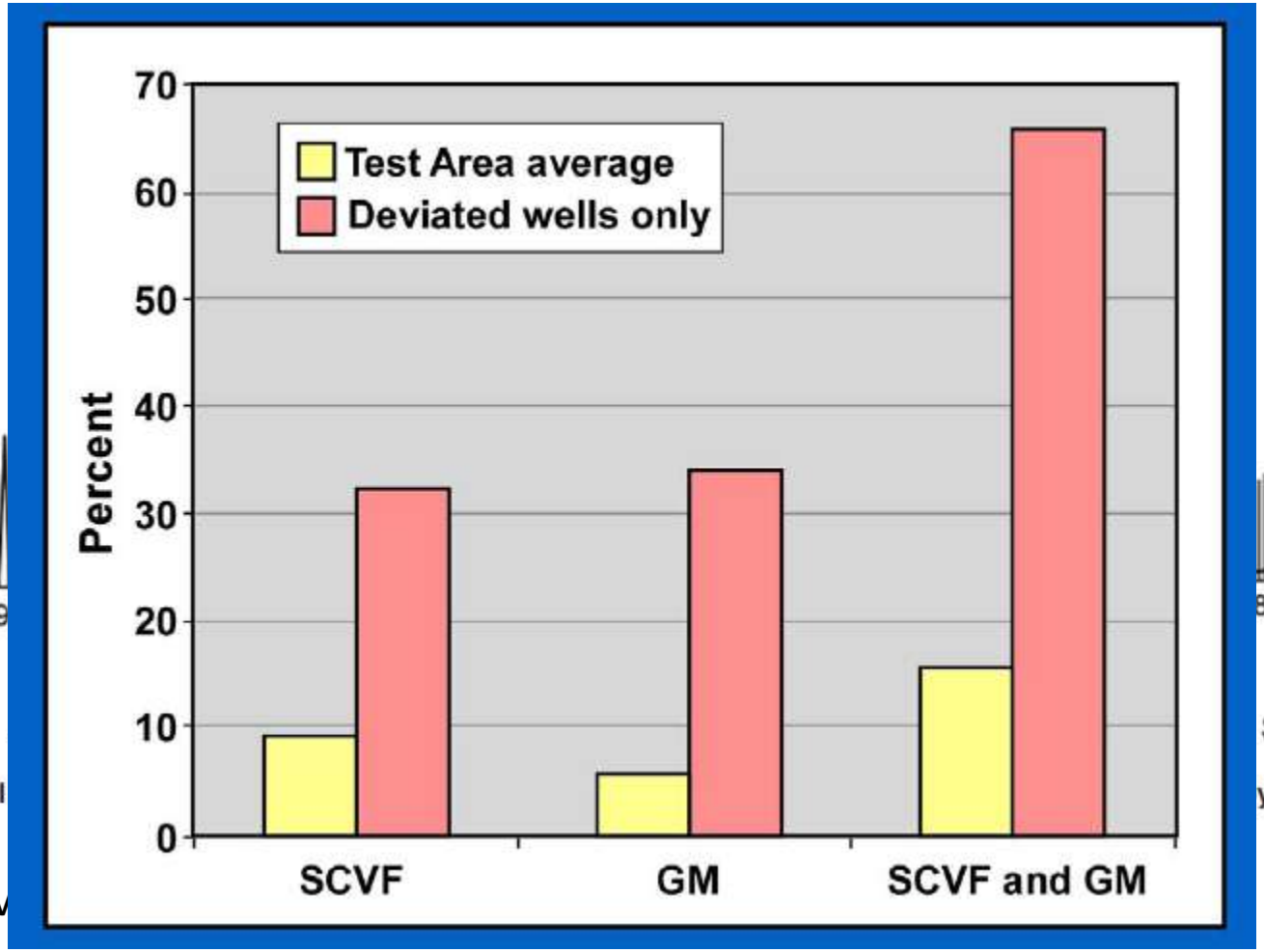
^ Wells with SCP by age. Statistics from the United States Mineral Management Service (MMS) show the percentage of wells with SCP for wells in the outer continental shelf (OCS) area of the Gulf of Mexico, grouped by age of the wells. These data do not include wells in state waters or land locations.

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

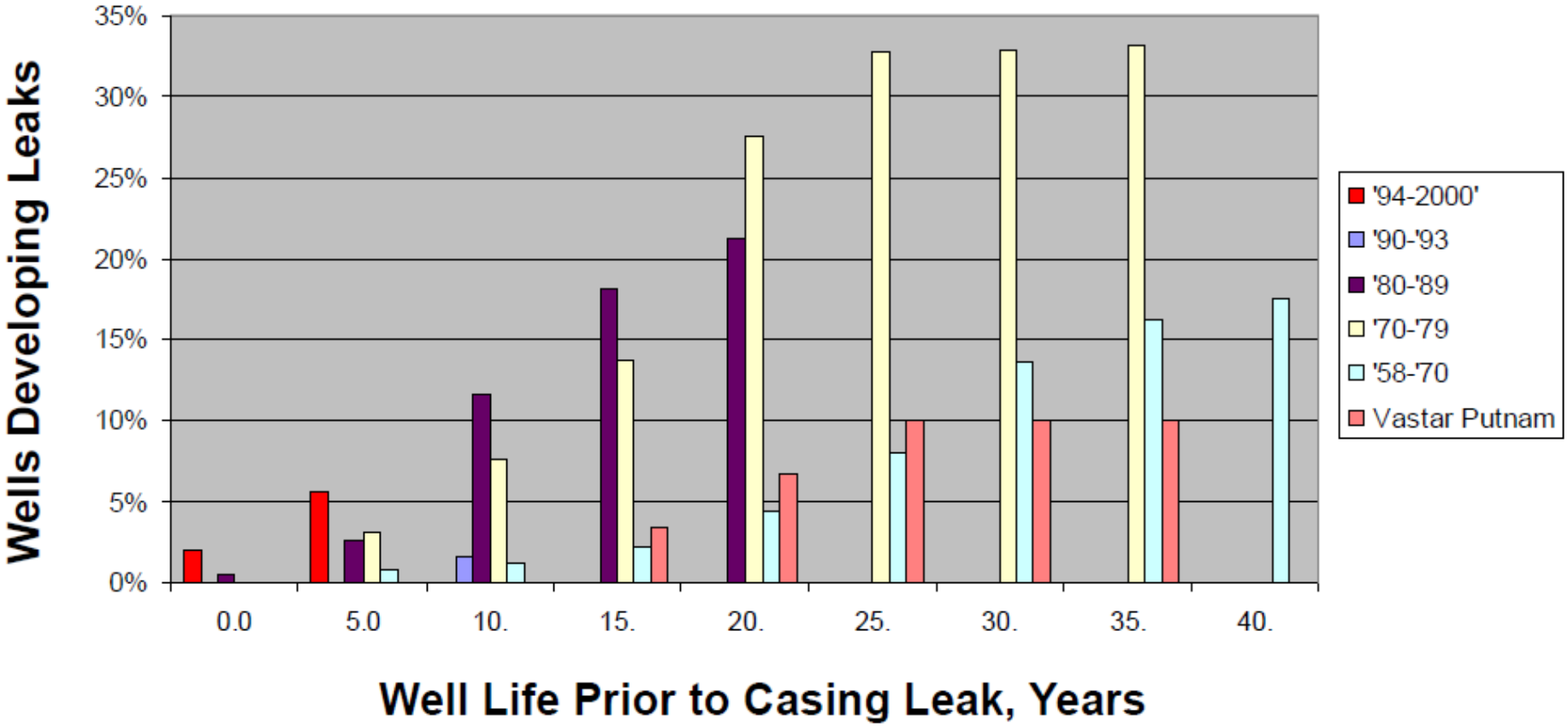
Brufatto *et al*., *Oilfield Review*, Schlumberger, Autumn, 2003

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



Watson and Bachu, SPE 106817, 2009.

Leaky Well Industry Statistics



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

What is the PA Marcellus Experience?

- **Created database** of inspection and violation records for over 41,000 gas and oil wells drilled in Pennsylvania since 2000
- Mined the data to identify all wells with wellbore integrity problems
- Statistically analyzed results: Cox Proportional Hazard Model to estimate future risk

"Assessment and Risk Analysis of Casing and Cement Impairment in Oil and Gas Wells In Pennsylvania: 2000-2012." Ingraffea *et al.* Paper currently under review.

The Well Database

• The database is based on spud reports from the PADEP Office of Oil and Gas Management web page available to the public.

• Conventional and unconventional gas, oil, combined gas and oil, and coalbed methane wells spudded from 01 Jan 2000 to 31 Dec 2012: **41,381 wells**

• All available compliance reports over the same time period. Reports provide data on inspection category (i.e. site, client, or facility), inspection type (e.g. administrative review, drilling, routine), inspection date, violations issued, and comments noted by the PADEP inspection staff regarding the inspection and/or violation(s) issued.

• 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.**

What is the PA Marcellus Experience?

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Search Procedure for Structural Integrity Problem Indicators : Three Filters

- Filter database for entries in “Violation Code” or “Violation Comment” fields in inspection reports

- Filter both the “Inspection Comment” and “Violation Comment” fields for most common keywords associated with failure of primary cement/casing or common remediation measures

- Keyword filter results then human-read thoroughly to confirm an indication of impaired well integrity

PA DEP Chapter 78 Violation Codes Used in 1st Filter

Violation Code (#)	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%**

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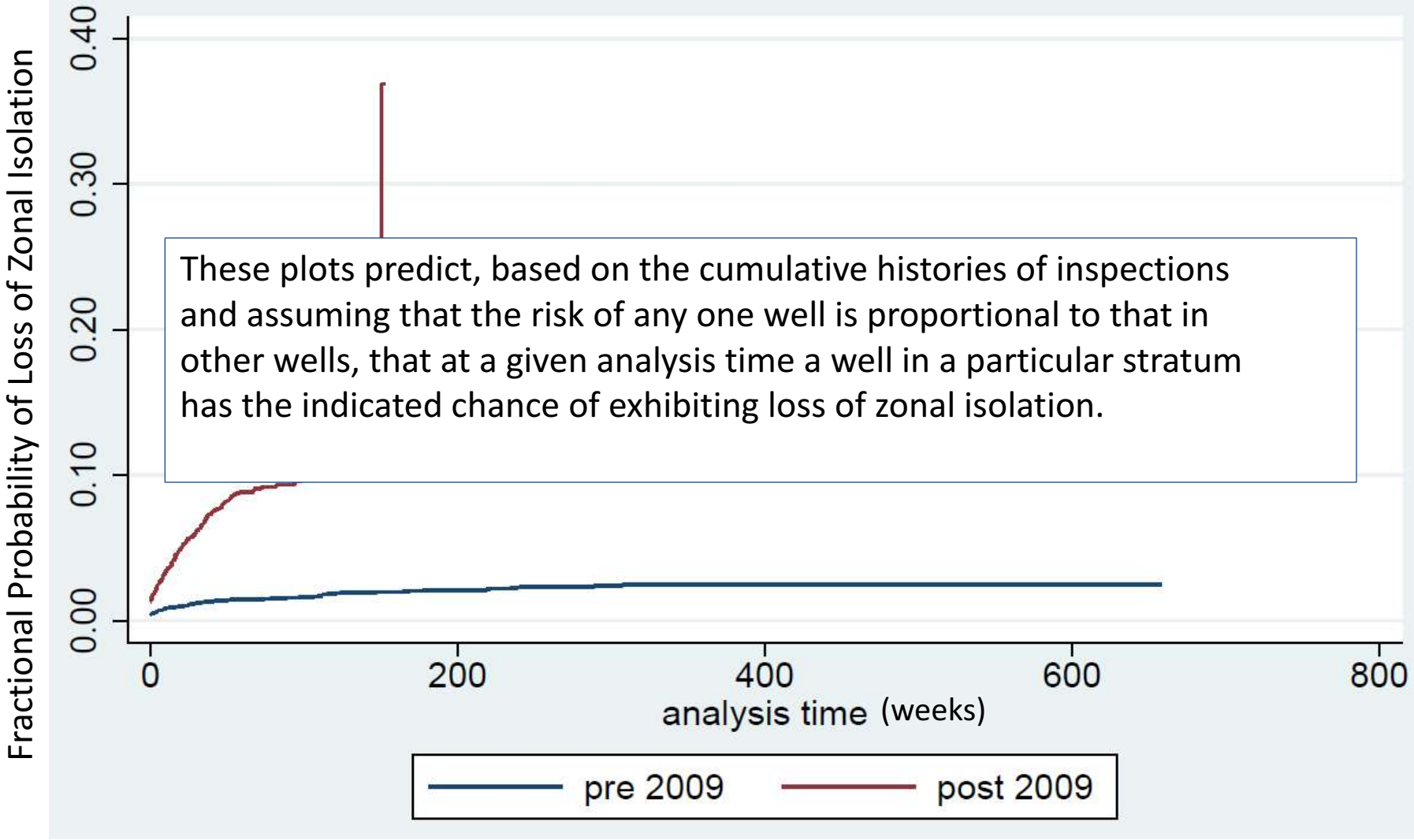
- Mined the data to identify all wells with wellbore integrity problems
- **Statistically analyzed results: Cox Proportional Hazard Model to estimate future risk**

Well Failure Rate Analysis

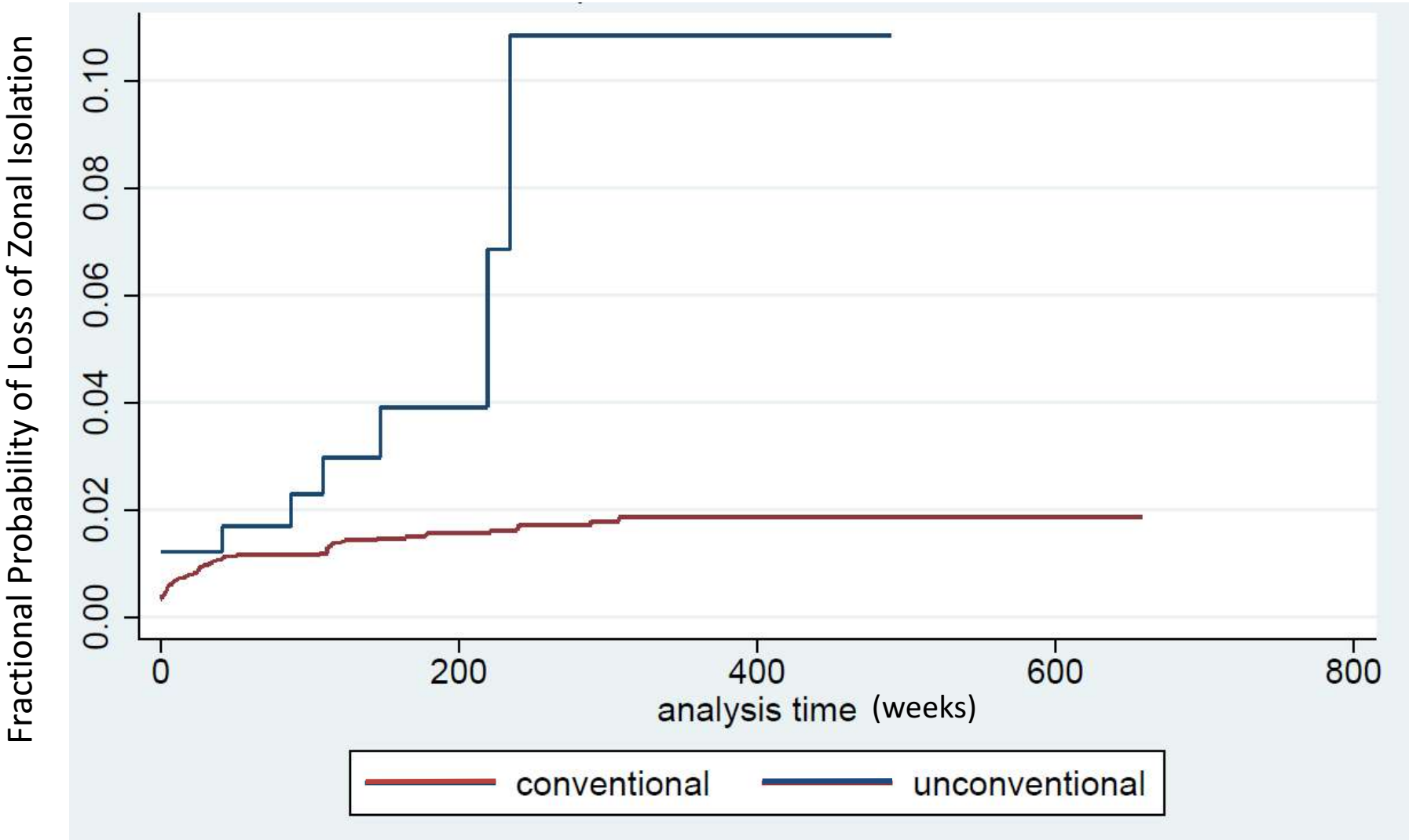
- **Cox Proportional Hazard Model to model well failure (hazard) rate**
- A multivariate regression technique to model the instantaneous risk of observing an event at time *t* given that an observed case has survived to time *t*, as a function of predictive covariates.
- Well type (i.e. unconventional 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.**

Comparison of Hazard Estimates for Pre- and Post-2009 Spudded Wells: Statewide Data

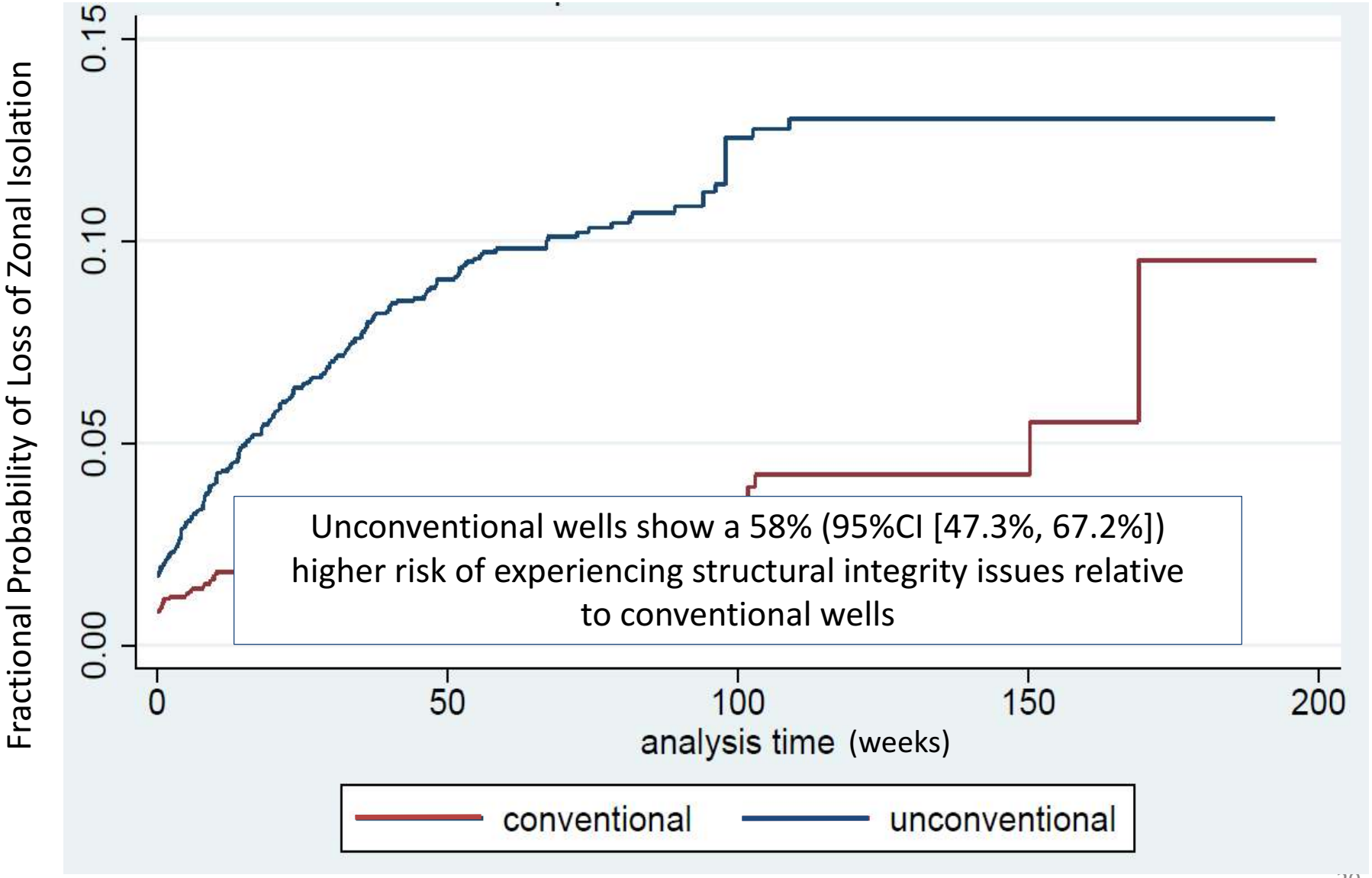


These plots predict, based on the cumulative histories of inspections and assuming that the risk of any one well is proportional to that in other wells, that at a given analysis time a well in a particular stratum has the indicated chance of exhibiting loss of zonal isolation.

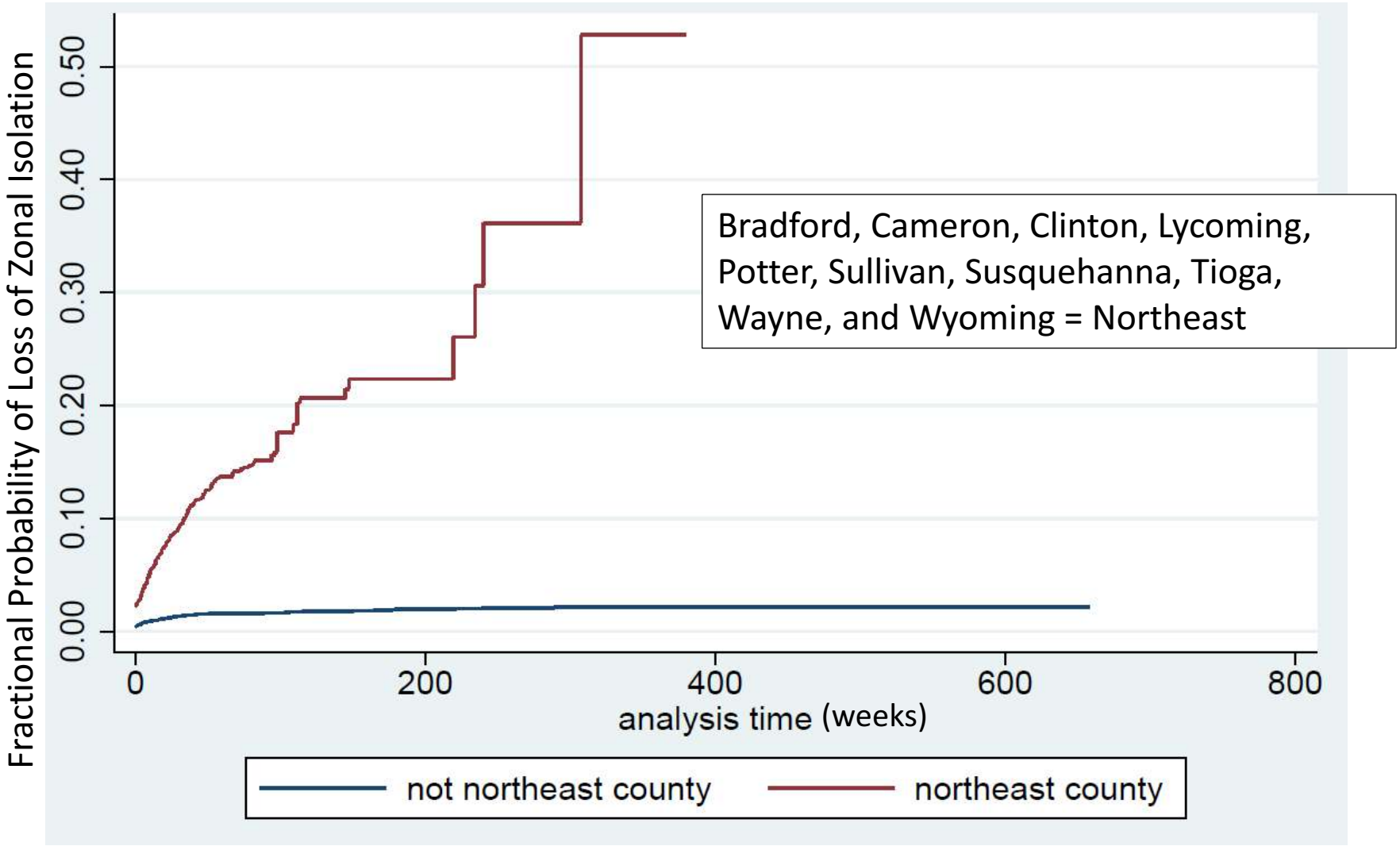
Comparison of Conventional and Unconventional Wells: Statewide, Pre-2009 Data



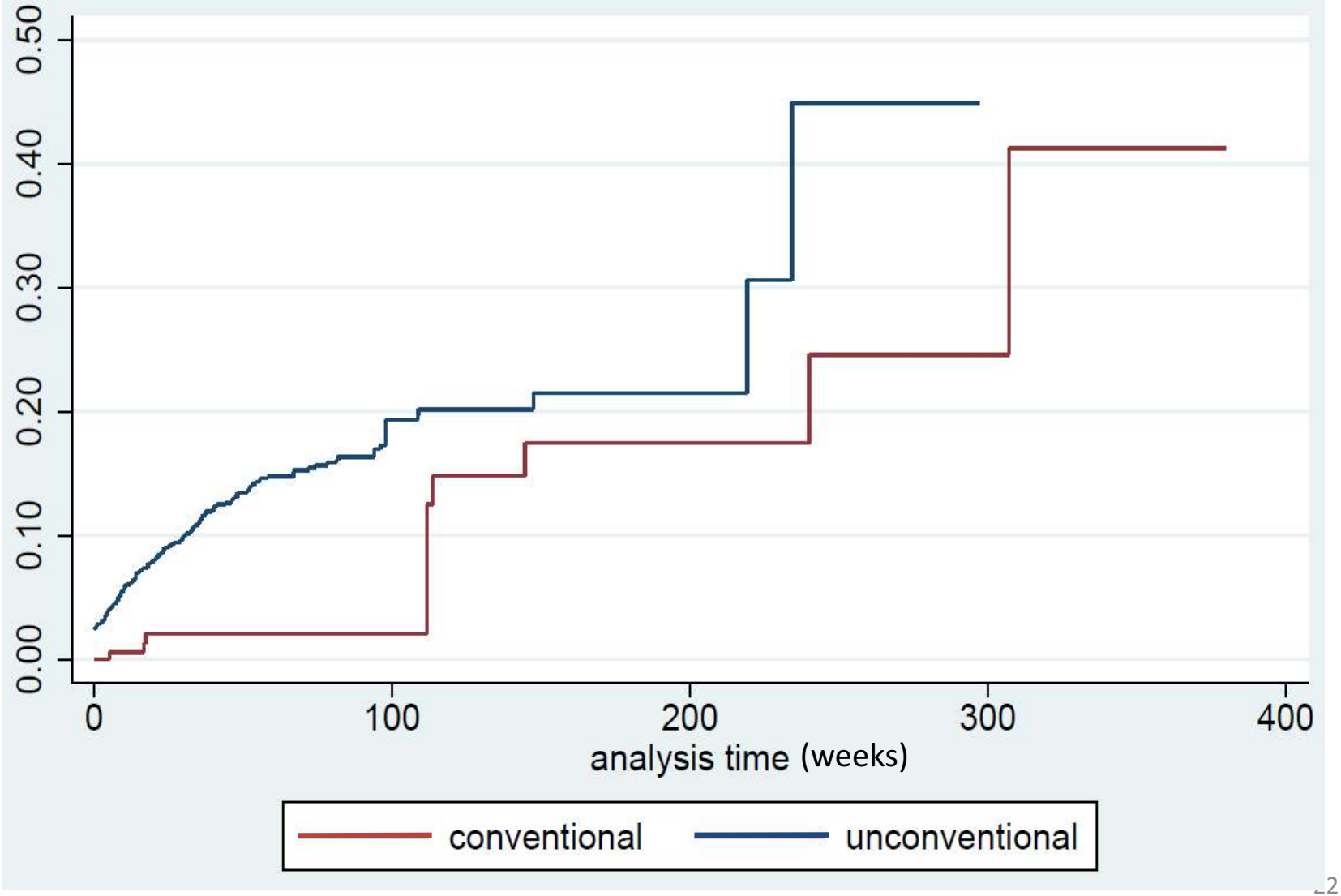
Comparison of Conventional and Unconventional Wells: Statewide, Post-2009 Data



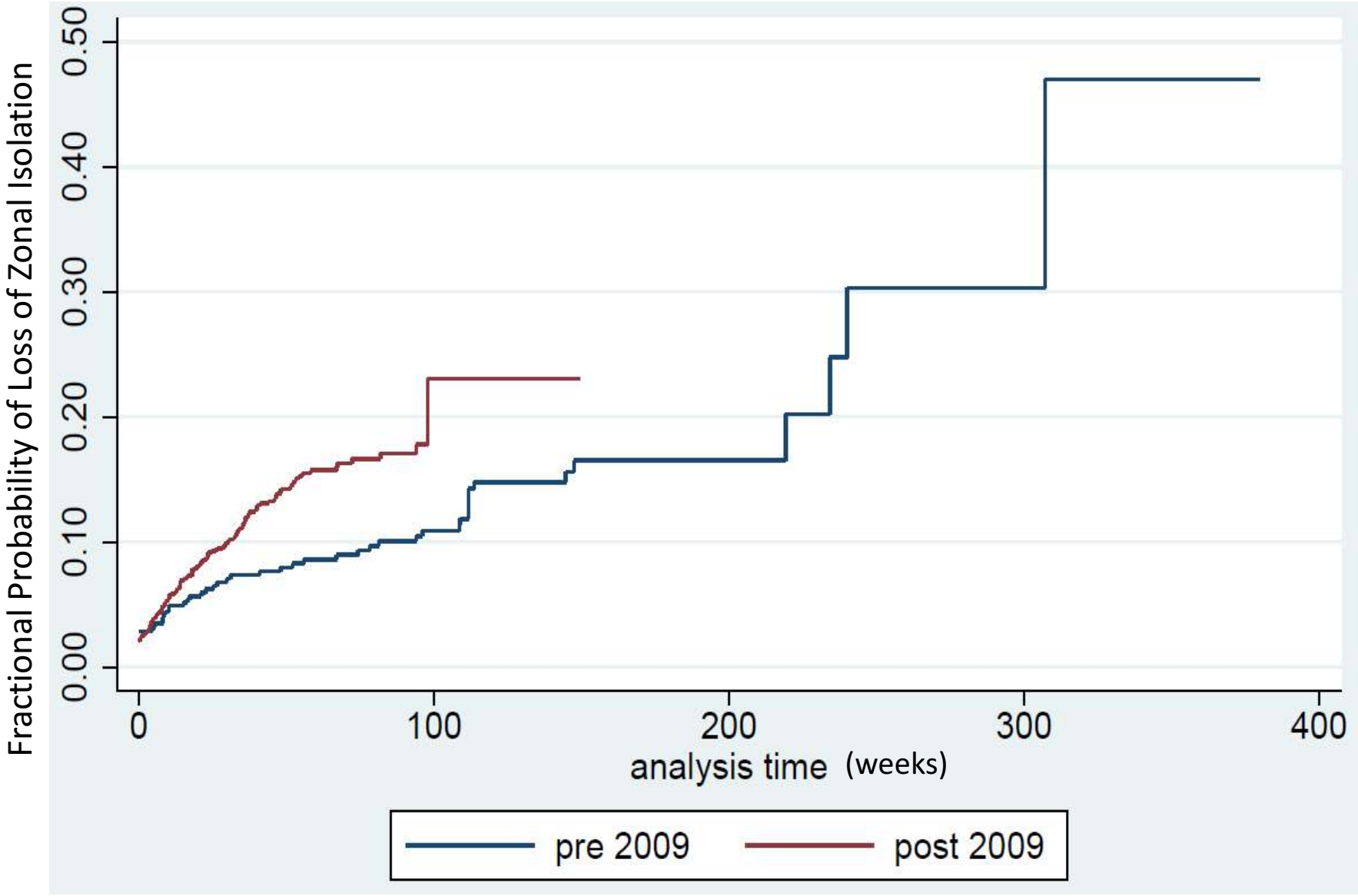
Comparison of Northeast to Non-Northeast Counties: All Wells



Comparison of Conventional to Unconventional Wells: Northeast Counties



Comparison of Northeast Counties, Pre- and Post-2009 Spuds



Observations and Conclusions

The Cox Proportional Hazard predictive process indicates that:

1. At least 13% of all Marcellus wells drilled statewide in PA since 2009 will experience loss of zonal isolation.
2. At least 45% of unconventional wells drilled in Northeast PA counties since 2009 will experience loss of zonal isolation.
3. Post-2009 unconventional wells in the Northeast PA counties will experience loss of zonal isolation at a higher rate than pre-2009 wells.

What Is Risk to Garrett/Allegany Counties?

- Take 90%* of 1086 sq. mi.= 977 sq. mi.
- Assume 8 wells/sq. mi. = 7,800 wells
- Assume 10%** will leak within 5 years = 780 leaking wells
- Impact on water wells?
- Impact on GHG emissions?

* Controlled by leasing, setbacks, zoning, etc.

** Conservative result from our risk assessment in PA Marcellus

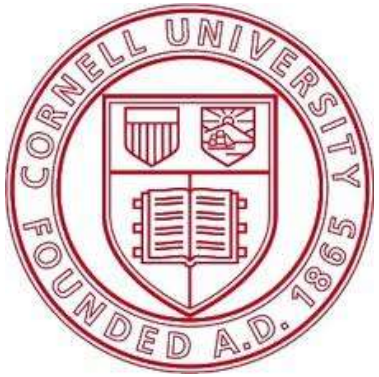
What Is Risk to Garrett/Allegany Counties?

Mitigation measures for impact on water wells

- Fewer gas/oil wells permitted: residential, commercial, park zones?
- Long setbacks from pads: 2,500 ft. in Dallas, TX
- Frequent inspections, tough enforcements: water well contamination can happen quickly
- More thorough inspection techniques: “bubbling” insufficient

Mitigation measures for impact on GHG emissions

- Frequent inspections, tough enforcements: life of well
- More thorough inspection techniques: GM can occur away from wellhead



Thank You

PSE

Physicians Scientists & Engineers for Healthy Energy