Assessment and Risk Analysis of Casing and Cement Impairment in Oil and Gas Wells in Pennsylvania: 2000-2012. Supplemental Information

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This supplemental information contains details on the Cox proportional hazards models and additional descriptive tables of the general and modeled datasets.

Cox Proportional Hazards Models

Definitions

The Cox proportional hazards model is a semi-parametric, multivariate analysis analogous to multiple regression. Certain aspects of the well inspection data - namely right-censoring and skewness – make the Cox proportional hazard model preferable to more traditional statistical models for this dataset. Right-censored data refers to data that is incomplete because an event occurrence is not noted for a subject during the time of observation either because the subject dropped out of observation (no further inspections on record) or because the data observation period ended.

Hazard Function - is defined as:

$$h(t)=lim_{\Delta t\to 0}\, Pr(t \leq T < t+ \Delta t \mid T\geq t) / \Delta t$$

where, *Pr* = probability of event and *T* = a nonnegative random variable representing the time until the outcome event of interest.

Thus, the hazard function describes the probability of an event of interest (impairment) occurring at time *t*, given that the event has not occurred before time *t.* Given the event time in the data, the hazard function can be estimated.

Cumulative Hazard - is the definite integral, from zero to the indexed time, of the hazard function. The Nelson-Aalen estimator is a nonparametric estimator of the cumulative hazard function based on a sample that is subject to right censoring. A cumulative hazard plot consists of plotting the cumulative hazard versus the event times and is quite routinely applied in censored data settings.

Cox Regression Model – specifies the hazard function of the time until the event of interest outcome, conditional on a set of *p* covariates $(X_1, X_2, \ldots, X_p)$, as

$$h(t \mid X_1, X_2, \ldots, X_p) = h_0(t)\exp(\beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_p X_p),$$

where exp(.) is the exponential function. The function $h_0(t)$ is called the baseline hazard rate and can be interpreted as the marginal hazard function that has not been adjusted by the covariates. The β_i $(i=1, \ldots, p)$ are regression coefficients.

Hazard Ratios – for the predictor variables are given by the exponent of the variable's regression coefficient, that is, $\exp(\beta_i)$ $(i=1, \ldots, p)$, and denote the relative risk of changes in the variables. Hazard ratios are interpreted as the multiplicative effect of a one unit increase in the variable of interest assuming all other variables hold constant.

Proportionality Assumption

A critical assumption in the model is that hazards are proportional; in other words the hazard ratio (HR) between any two observations is constant regardless of the time or the value of any covariate. Proportionality is tested as described in Grambsch, PM and Therneau TM (1994). Results of the test are presented in Table S1. The proportional hazards assumption holds for individual covariates (p = 0.06 and 0.09). Proportionality also holds for the inspection count covariate in the Pre-2009 stratum (p = 0.46) and well type and inspection count covariates in the Post-2009 stratum (p = 0.75 and 0.44, respectively) Proportionality is violated in the Pre-2009 stratum for well type covariate due to the small number of unconventional wells in this stratum. A nominal p-value of 0.05 is generally accepted as a minimum for passing this test. Analysis of the geographic stratum uses the log-rank test and does not assume proportionality.

Table S1. *Test of Proportional Hazards.*

Covariate/Stratum	rho	chi^2	df	Prob>chi^2
Full Dataset				
X2_WELLTYPE	0.0831	3.53	1	0.0602
X3_LIFEINSP	0.15105	2.76	1	0.0969
PRE 2009 Spuds				
X2_WELLTYPE	0.17451	5.17	1	0.0229
X3_LIFEINSP	0.07931	0.55	1	0.4588
2009 - 2012 Spuds				
X2_WELLTYPE	0.01744	0.11	1	0.7457
X3_LIFEINSP	-0.0857	0.6	1	0.4371

Variables

Analysis time - a measure of the time of observation, (i.e. the period, in weeks, between the date of the first inspection of the well and the date of either the last known inspection or the first occurrence of an indicator in the inspection history of the well). As the dependent variable, time cannot be a null or negative value. All wells in the dataset enter observation at $t = 0$ regardless of what year they were spudded. Thus, staggered times of entry into the analysis are normalized and time-dependencies related to spud year are overcome. Descriptive statistics of analysis time for spud years are given in table S2.

Observation continues until the last date of inspection or the occurrence of a cement/casing indicator in the well's inspection history. Individual wells exit observation if either an indicator event is found (see *event status*) or if the time of observation for the well expires with no indicator events found.

Table S2. *Time of analysis by spud year in weeks, modeled data. Mean time of analysis for the dataset is 91.46 weeks (0.14 – 675.29).*

Spud Year	*Mean*	*Median*	*Standard Deviation*	*Minimum*	*Maximum*	*Well Count*
2000	143.862	44.571	205.003	0.143	675.286	1216
2001	134.268	48.286	185.063	0.143	616.000	1583
2002	146.253	47.786	184.081	0.143	565.429	1302
2003	120.863	31.143	161.539	0.143	513.000	1675
2004	108.051	33.000	139.024	0.143	467.857	1985
2005	108.996	29.429	131.599	0.143	411.429	2557
2006	99.886	43.143	111.471	0.143	361.143	2870
2007	85.387	46.786	92.920	0.143	308.571	3154
2008	77.720	56.714	74.957	0.143	254.143	3144
2009	76.941	74.143	59.112	0.143	204.429	1909
2010	64.337	65.786	43.142	0.143	154.000	2182
2011	39.279	37.000	25.268	0.143	101.286	2155
2012	15.197	11.429	12.939	0.143	48.000	1211

Event Status – is a logical binary (0 = N; 1 = Y) value describing whether an individual well experienced an indicator of loss of structural integrity at any time during the analysis. Individual wells are "censored" if the observation is incomplete for any reason independent of the "event" (i.e. the reason for the incomplete observation is non-informative). For example, we know that some wells in our dataset will either leave observation because there are simply no more inspections on record for a given well, or that a well integrity issue for a given well was never documented throughout the analysis time. In these cases the event simply didn't occur over the observation time (01 Jan 2000 – 31 Dec 2012) or we lost track of a well's status before the end of the analysis time due to lack of inspections. We don't know when or if these wells will show indications of failure, only that as of Dec 31 2012, there were no documented indications of casing or cement issues. Thus, we can't know the actual survival time of such wells. These wells are termed "censored" to indicate that the period of observation was cut off before the event happened.

Well Type (X2_Welltype) **–** a time-independent predictor variable reflecting whether the well type, as classified by PADEP, is conventional or unconventional. The variable is entered into the model as a categorical variable, where conventional well = 0, unconventional well = 1. Well type distribution is given in Table S3.

Table S3*. Annual spuds and inspections reported by PADEP: 2000-2012, full dataset.*

Spud Year	**Spudded Wells**			**Inspected Wells**			**%**
	Conv.	**Unconv.**	**TOTAL**	**Conv.**	**Unconv.**	**TOTAL**	**Inspected**
2000	1637	0	1637	1389	0	1389	84.85%
2001	2248	0	2248	1827	0	1827	81.27%
2002	2136	1	2137	1564	1	1565	73.23%
2003	2657	4	2661	1940	4	1944	73.06%
2004	3039	2	3041	2308	2	2310	75.96%
2005	3906	6	3912	2949	6	2955	75.54%
2006	4579	23	4602	3307	23	3330	72.36%
2007	4768	97	4865	3461	83	3544	72.85%
2008	4526	321	4847	3337	304	3641	75.12%
2009	1987	794	2781	1620	749	2369	85.19%
2010	1648	1560	3208	1345	1532	2877	89.68%
2011	1232	1888	3120	1055	1862	2917	93.49%
2012	1011	1311	2322	813	1197	2010	86.56%
SUM	**35374**	**6007**	**41381**	**26915**	**5763**	**32678**	**78.97%**

Inspection Count (X3_LifeInsp) – a predictor variable which reflects the total number of inspections on record for a given well. One measurement per unique well was made, thus, while wells may accumulate more inspections outside the time period of the study, this variable is time-independent. The number of inspections per well ranges from 1 to 86 with an average value of 2.75. Inspection count frequencies are reported in Table S4.

***Table S4**. Frequency of inspection counts, modeled data.*

X3_LIFEINSP	Freq.	Percent	Cum.	X3_LIFEINSP	Freq.	Percent	Cum.%
1	10395	37.86%	37.86%	**20**	8	0.03%	99.76%
2	6730	24.51%	62.37%	**21**	6	0.02%	99.78%
3	4106	14.96%	77.33%	**22**	10	0.04%	99.82%
4	2238	8.15%	85.48%	**23**	7	0.03%	99.84%
5	1292	4.71%	90.19%	**24**	6	0.02%	99.87%
6	827	3.01%	93.20%	**25**	4	0.01%	99.88%
7	521	1.90%	95.10%	**26**	3	0.01%	99.89%
8	364	1.33%	96.42%	**27**	6	0.02%	99.91%
9	244	0.89%	97.31%	**28**	6	0.02%	99.93%
10	201	0.73%	98.04%	**29**	1	0.00%	99.94%
11	123	0.45%	98.49%	**30**	4	0.01%	99.95%
12	89	0.32%	98.82%	**31**	3	0.01%	99.96%
13	63	0.23%	99.05%	**33**	2	0.01%	99.97%
14	49	0.18%	99.22%	**34**	1	0.00%	99.97%
15	47	0.17%	99.40%	**35**	3	0.01%	99.99%
16	39	0.14%	99.54%	**36**	1	0.00%	99.99%
17	16	0.06%	99.60%	**44**	1	0.00%	99.99%
18	20	0.07%	99.67%	**51**	1	0.00%	100.00%
19	17	0.06%	99.73%	**86**	1	0.00%	100.00%
				Total	**27455**	**100.00%**	

Model Inputs

The modeled dataset is built from Pennsylvania Department of Environmental Protection (PADEP) Office of Oil and Gas spud reports for production wells spudded between Jan 01, 2000 to Dec 31, 2012 (41,381 wells). These wells are matched to PADEP compliance reports for site inspections carried out over the same time period using API well identifiers. Only inspected wells are used in the Cox model. For our well inventory of 41,381 wells, 8,703 wells have no record of inspection (Table S3). An additional 5,223 wells in the dataset have negative (days to first inspection since spud) time values and cannot be modeled. We assume that either incorrect spud dates or incorrect inspection dates were entered for these wells and remove these wells from the modeled dataset. The resulting modeled dataset contains 27,455 unique wells (22,919 conventional; 4,536 unconventional wells), representing 75,505 inspections. Well counts for the modeled dataset by well type and county are given in Table S5.

Table S5. *Distribution of wells by county and well type, modeled data. Bold indicates a county within the NE County stratum*

COUNTY	Conv. Wells	Unconv. Wells	Total	COUNTY	Conv. Wells	Unconv. Wells	Total
Allegheny	292	7	299	Huntingdon	3	1	4
Armstrong	2274	87	2361	Indiana	1336	21	1357
Beaver	2	8	10	Jefferson	1563	21	1584
Blair	0	1	1	Lawrence	44	8	52
Bradford	**14**	**937**	**951**	**Lycoming**	**0**	**455**	**455**
Butler	115	121	236	McKean	3657	38	3695
Cambria	122	4	126	Mercer	1303	1	1304
Cameron	**11**	**11**	**22**	**Potter**	**167**	**57**	**224**
Centre	207	34	241	Somerset	17	13	30
Clarion	1302	15	1317	**Sullivan**	**0**	**32**	**32**
Clearfield	656	105	761	**Susquehanna**	**2**	**447**	**449**
Clinton	**50**	**58**	**108**	**Tioga**	**9**	**707**	**716**
Crawford	900	0	900	Venango	777	2	779
Elk	390	45	435	Warren	2045	4	2049
Erie	185	0	185	Washington	348	517	865
Fayette	1422	151	1573	**Wayne**	**1**	**1**	**2**
Forest	1290	6	1296	Westmoreland	1954	160	2114
Greene	460	391	851	**Wyoming**	**1**	**70**	**71**
				Total	**22919**	**4536**	**27455**

Impairment Indicators

Inspection reports were filtered according to inspection comment keywords related to cement/casing integrity and relevant violations noted. Individual wells are often associated with multiple comment and violation indicators over the course of their inspection history. For modeling purposes we track only the first instance of an indicator in the well's inspection history and individual wells are associated with only one indicator category (violation or comment). Indicators in both categories are grouped into indicator bins based on generalized implications of the keywords or violation codes. Detailed lists of indicators of impairment used in the filtering and the counts of individual wells associated with each comment and violation indicator bin, are given in Tables S6 and S7, respectively.

Comment indicators presented in table S6 are considered confirmed losses of cement or casing integrity as these indicators reflect an observed and/or measured stray gas flow through annuli, remediation procedures aimed at stopping the flow of stray gas, or operator confirmation of a cement/casing defect.

Violation indicators are less certain in terms of confirming loss of integrity in part because the intent of specific regulatory provisions associated with the violation codes is often precautionary. For example, violations for inadequate casing may be noted prior to the installation of the casings (i.e. casing strings stored on site are found to not be up to regulatory specifications, resulting in subsequent delivery and installation of new casing strings within the appropriate specifications). Pressure control violations may reflect observed over-pressuring or simply the absence of mandated pressure gauges. Information necessary to filter out precautionary violations is often not available, though inspection and violation comments were reviewed when available in an attempt to limit violations, as much as possible given the available data, to confirmed losses of well integrity. Still, precautionary violations may precede more certain indicators noted in later inspections. Additional violations which provide stronger evidence of impairment, such as those related to defective cement or failure to prevent migration of fluids and gases to groundwater, may also be cited within the same inspection (multiple violations cited in a single inspection record) or later inspections. Because the model tracks only the first occurrence of an indicator, precautionary violations must be filtered out carefully and the full history of an individual well considered before deciding whether to ignore what might seem inconsequential. We have made every attempt to ensure that the full history of wells modeled is considered during filtering of the violations.

One way to assess validity of violation indicators is to compare the counts of "Administrative" and "Environmental Health & Safety" violations, though this method has caveats, including the limits of first occurrence indicators noted above. While administrative violations are often associated with reporting, permitting, and precautionary infractions, there are administrative violations, such as 78.86 (Failure to report defective, insufficient, or improperly cemented casing w/in 24 hrs or submit plan to correct w/in 30 days), which are strong indicators of a loss of wellbore integrity. Of the 102 individual modeled wells associated with violation code 78.86, inspection and/or violation comments confirm bubbling and/or annular gas for 57 of the wells. In total, administrative violations make up 307 of the 367 violation indicators to individual wells; 22% of these administrative violations include violation or inspection comments which confirm well impairment and an additional 7.2% of these are associated with comments or additional violations from follow-up inspections which confirm well impairment.

Table S6. *Indicators of loss of structural integrity event: keywords used in the indicator filtering of inspection comments and count of unique wells for which an indicator is noted. Counts denote the number of individual wells associated with at least one of the indicators listed and do not represent the cumulative occurrence of the indicator in the inspection histories.*

Bin	Description	Keywords	Count
SCP	Sustained casing pressure is either observed as gas bubbling at the surface or indicated by SCP tests (pressure bled followed by re-pressurization).	“bubbling”, “bubbl*”,“bleed”, “bled down”	70
Annular Gas	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”	20
Cement Squeeze	Remedial cementing operation performed to repair inadequate 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 barrier integrity.	“squeeze”, “squeeze*”, “eeze”, “perf and patch”, “perf”	34
Top Job	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"	17
Other	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*”	4

** Indicates a search where “*” represents zero or more of any additional characters within the string*

Table S7. *Indicators of loss of structural integrity event: violation codes in PADEP inspection reports indicating a loss of structural integrity with count of unique wells receiving the violation. Violation codes reported by PADEP inspectors are corrected as per violation comments where appropriate. Counts denote individual wells receiving at least one of the violations listed and do not represent the total number of violations related to cement/casing integrity across all wells.*

Violation Codes	Description/Bin	Count
78.73A; 78.73(b); 78.81(a)(2); 607.207; 210INADPLUG	Failure to prevent migrations to fresh groundwater	24
207B	Failure to case and cement to prevent migrations into fresh groundwater	11
78.85; 78.86	Defective, insufficient, or improperly installed cement	120
78.82; 78.83; 78.83GRNDWTR; 78.84; 209CASING	Defective, insufficient, or improperly installed casing	80
78.81D2; 78.83; 78.83COALCSG; 79.12	Defective, insufficient, or improperly installed casing or cement	49
78.73B; 78.81D1	Pressure control	82
210NCPLUG	Inadequate plugging	1

Comment and violation indicator counts reported in Tables S6 and S7 reflect singular occurrences of a cement/casing indicator for an individual well. As such, these counts are indicative of the number of wells which are likely exhibiting impairment issues, but not the prevalence of the indicator categories or individual indicator bins. In the following section, we discuss the distribution of accumulated indicators over time since first inspection and compare geographic strata.

Distributions of total inspection comment indicators for the NE and non-NE counties by time since first inspection are presented in Figures S1 and S2. Counts across the time-series reflect the accumulation of indicator counts over time.

Figure S1. *Distribution of total inspection comment indicators for northeast (top) and non-northeast counties (bottom) over time. Time denotes the time increment in which the indicator was noted relative to the date of first inspection.*

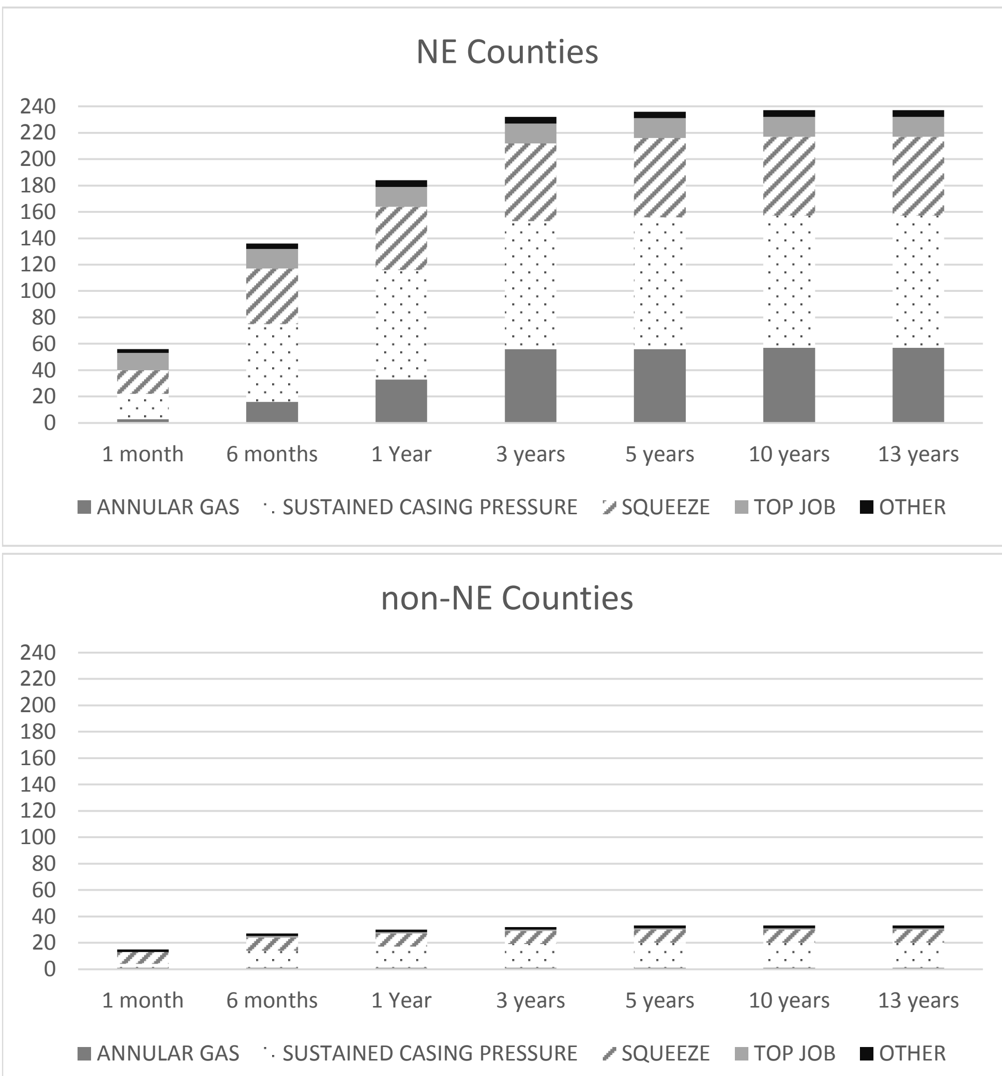
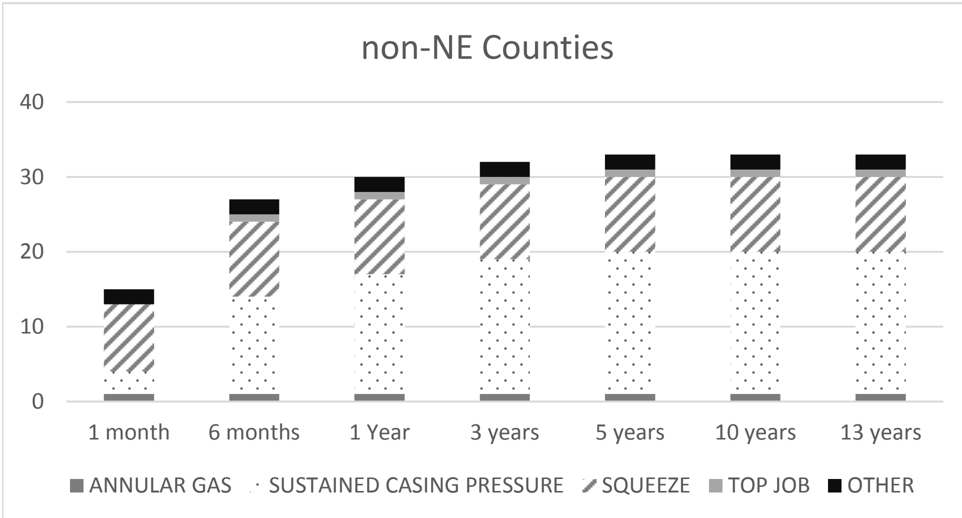


Figure S2. *Detailed view of distribution of total inspection comment indicators non-northeast counties over time. Time denotes the time increment in which the indicator was noted relative to the date of first inspection.*

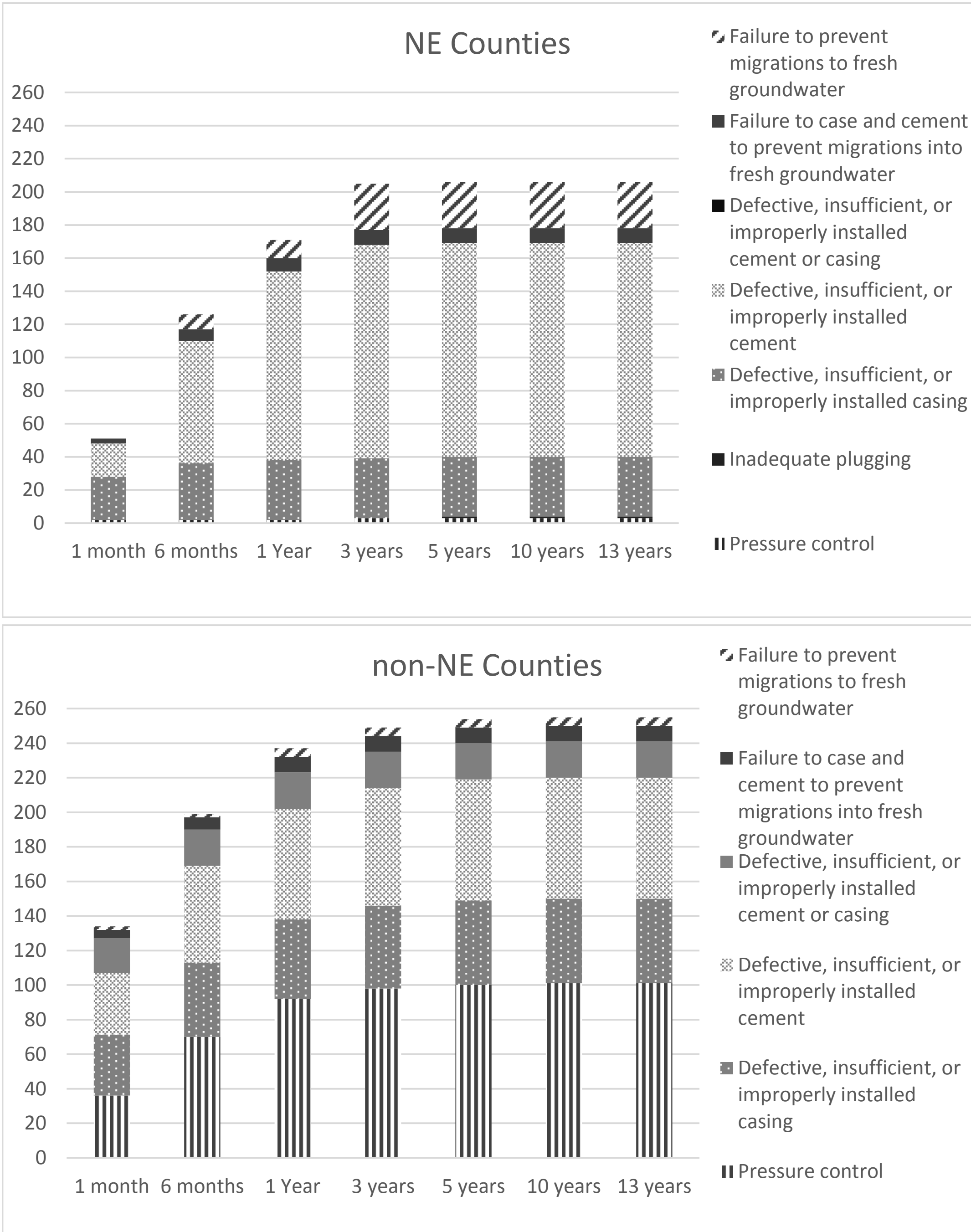


Total comment indicators are, on average, 6.2 times higher (3.7 – 7.2 across all time frames) in the NE counties group, relative to the non-NE counties group. Higher incidence of sustained casing pressures and annular gas in the NE counties make up two-thirds of this difference with the remainder largely accounted for by a higher occurrence of remediation work (squeeze, top job) in the NE inspections. Growth in the occurrence of remediation indicators in the NE counties over time is also noted (+32% at year 5 relative to the 6 month value), whereas remediation indicators in the non-NE group peak at the 6-month increment with no additional remediation indicators noted thereafter. Figure S2 shows the distribution of comment indicators for the non-NE counties in detail.

Regional differences in total violation indicators are not as pronounced, though there are substantial differences in the relative contributions of individual violation indicator bins (Figure S3), notably the "Failure to prevent migrations into fresh groundwater" and "Defective, insufficient, or improperly installed cement bins." The first of these bins (migration) is made up of the following violation codes: 78.73A - Operator shall prevent gas and other fluids from lower formations from entering fresh groundwater; 78.73(b) - In case of excessive casing seat pressure, operator shall take action to prevent the migration of gas and other fluids from lower formations into fresh groundwater; 78.81(a)(2) - Failure to prevent migration of gas or other fluids into sources of fresh groundwater; 607.207 - Failure to prevent gas migration into sources of fresh groundwater; and 210INADPLUG - Leaking plug or failure to stop vertical flow of fluids. Loss of well integrity is confirmed in any well receiving one or more of these violations and has either already caused or will likely cause migration of subsurface fluids. The second bin (defective cement; 78.86 - Failure to report defective, insufficient, or improperly cemented casing w/in 24 hours or submit plan to correct w/in 30 days and 78.85 - Inadequate, insufficient, and/or improperly installed cement) is also a priority indicator for loss of well integrity. As previously discussed, inspection comments accompanying the 78.86 violation code often confirm the presence of annular gas flows and the loss of well integrity. Violation code 78.85 occurs less often in the inspection record (18 individual wells) and frequently lacks the additional data required to confirm a loss of integrity.

Accumulated counts of violation indicators within the migration bin in the NE are small relative to other indicator bins for the region, but still 5.5 times higher than that of the non-NE group by the 13 year time increment. Accumulated counts from the defective cement bins are 1.8 times higher by the end of the analysis time. The occurrence of violations in both bins peaks in the NE counties in the third year since the first inspection, with a 155% and 13.2% increase in migration and defective cement violations, respectively, relative to counts at the end of year one.

Figure S3. *Distribution of total violation indicators for northeast (top) and non-northeast counties (bottom). Time denotes the time increment in which the indicator was noted relative to the date of first inspection. Individual violation codes are grouped by violation bin.*



Model Outputs

Tables S8-S13 present complete outputs for each model run. Hazard ratio (HR) reflects the estimated change in hazard from baseline with a one unit change in covariate. An HR of 1 is interpreted as no effect due to changes in the covariate. Well type covariate is a logical binary, thus HR reflects the change in hazard for the alternative well type relative to the default well type. Default well type in the temporal strata is 1 (HR reflects the change from unconventional to conventional). Default value in the geographic strata is 0 (HR reflects a change from conventional to unconventional well). Inspection count is a continuous variable, thus hazard responds logarithmically. HR in the inspection count covariate, *x*, reflects the estimated increase in hazard for per unit increase of *x*.

Table S8. Cox model results: Pre-2009 stratum

stcox X2_WELLTYPE_rev X3_LIFEINSP if **pre_2009==1**

failure _d: EVENT

analysis time _t: t_out_newest

Iteration 0:	log likelihood =	-1488.33
Iteration 1:	log likelihood =	-1424.59
Iteration 2:	log likelihood =	-1423.95
Iteration 3:	log likelihood =	-1423.94
Iteration 4:	log likelihood =	-1423.94

Refining estimates:

Iteration 0:	log likelihood =	-1423.94

Cox regression -- Breslow method for ties

No. of subjects =	19647
Number of observations =	19647
Number of events =	161
Time at risk =	1345453.714
Log likelihood =	-1423.9414
LR chi2(2)	128.79
Prob > chi2	0.000

Covariate	Coefficient	Std.Err.	z	P>|z|	HR	HR 95% CI	
X2_WELLTYPE	-0.070	0.340	-0.210	0.837	0.933	0.479	1.816
X3_LIFEINSP	0.163	0.010	16.230	0.000	1.177	1.154	1.201

Table S9. Cox model results: Post-2009 stratum

stcox X2_WELLTYPE_rev X3_LIFEINSP if **pre_2009==0**

failure _d: EVENT

analysis time _t: t_out_newest

Iteration 0:	log likelihood =	-2933.35
Iteration 1:	log likelihood =	-2894.79
Iteration 2:	log likelihood =	-2873.7
Iteration 3:	log likelihood =	-2871.48
Iteration 4:	log likelihood =	-2871.35
Iteration 5:	log likelihood =	-2871.35
Refining estimates:		
Iteration 0:	log likelihood =	-2871.35

Cox regression -- Breslow method for ties

No. of subjects =	**7808**
Number of observations =	7808
Number of events =	**351**
Time at risk =	275433.8574
Log likelihood =	-2871.3541
LR chi2(2)	123.99
Prob > chi2	0.000

Covariate	Coefficient	Std. Err.	z	P>|z|	HR	HR 95% CI	
X2_WELLTYPE	-0.860	0.131	-6.580	0.000	0.423	0.328	0.547
X3_LIFEINSP	0.057	0.005	11.280	0.000	1.059	1.048	1.069

68 **Table S10**. Cox model results: NE County vs Non-NE County

stcox ne_county

failure _d: EVENT

analysis time _t: t_out_newest

Iteration 0:	log likelihood =	-4903.356
Iteration 1:	log likelihood =	-4830.052
Iteration 2:	log likelihood =	-4736.217
Iteration 3:	log likelihood =	-4654.865
Iteration 4:	log likelihood =	-4651.072
Iteration 5:	log likelihood =	-4651.071
Refining estimates:		
Iteration 0:	log likelihood =	-4651.071

Cox regression -- Breslow method for ties

No. of subjects =	27455.000
Number of observations =	27455.000
Number of events =	512.000
Time at risk =	1620887.571
LR chi2(1) =	504.570
Log likelihood =	-4651.071
Prob > chi2 =	0.000

_t	Haz. Ratio	Std. Err.	z	P>|z|	[95% Conf. Interval]	
ne_county	8.536	0.766	23.890	0.000	7.159	10.178

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70 **Table S11**. Cox model results: NE County, well type

stcox X2_WELLTYPE if **ne_county ==1**

failure _d: EVENT

analysis time _t: t_out_newest

Iteration 0:	log likelihood =	-1936.948
Iteration 1:	log likelihood =	-1931.068
Iteration 2:	log likelihood =	-1930.583

Iteration 3: log likelihood = -1930.577

Iteration 4: log likelihood = -1930.577

Refining estimates:

Iteration 0: log likelihood = -1930.577

Cox regression -- Breslow method for ties

No. of subjects =	3030.000
Number of observations =	3030.000
Number of events =	266.000
Time at risk =	115866.857
LR chi2(1) =	12.740
Log likelihood =	-1930.577
Prob > chi2 =	0.000

_t	Haz. Ratio	Std. Err.	z	P>|z|	[95% Conf. Interval]	
X2_WELLTYPE	2.657	0.842	3.080	0.002	1.428	4.946

Table S12. Cox model results: NE County, inspection count

stcox X3_LIFEINSP **if ne_county ==1**

failure _d: EVENT

analysis time _t: t_out_newest

Iteration 0:	log likelihood =	-1936.948
Iteration 1:	log likelihood =	-1929.354
Iteration 2:	log likelihood =	-1919.131
Iteration 3:	log likelihood =	-1918.171
Iteration 4:	log likelihood =	-1918.159
Iteration 5:	log likelihood =	-1918.159

Refining estimates:

Iteration 0: log likelihood = -1918.1591

Cox regression -- Breslow method for ties

No. of subjects = 3030

Number of observations = 3030
Number of events = 266
Time at risk = 115866.857
LR chi2(1) = 37.580
Log likelihood = -1918.159
Prob > chi2 = 0.000

_t	Haz. Ratio	Std. Err.	z	P>|z|	[95% Conf. Interval]	
X3_LIFEINSP	1.065	0.009	7.240	0.000	1.047	1.083

Table S13. Cox model results: NE County, pre/post 2009 spuds

stcox post_2009 **if ne_county ==1**
failure _d: EVENT
analysis time _t: t_out_newest

Iteration 0: log likelihood = -1936.948
Iteration 1: log likelihood = -1932.630
Iteration 2: log likelihood = -1932.590
Iteration 3: log likelihood = -1932.590
Refining estimates:
Iteration 0: log likelihood = -1932.590

Cox regression -- Breslow method for ties
No. of subjects = 3030.000
Number of observations = 3030.000
Number of events = 266.000
Time at risk = 115866.857
LR chi2(1) = 8.720
Log likelihood = -1932.590
Prob > chi2 = 0.003

_t	Haz. Ratio	Std. Err.	z	P>|z|	[95% Conf. Interval]	
post_2009	1.580	0.255	2.840	0.005	1.152	2.167

Pre-Modeled Data, Detailed

Table S14 presents the detailed impairment rates from the dataset by spud year and well type prior to modeling used in preparing table 1 of the main text.

Table S14. Conventional, unconventional, and state total oil and gas wells with indicators of loss of structural integrity noted in PADEP state inspection reports: 2000-2012*, full dataset.

	Conventional Wells			Unconventional Wells			Statewide Total		
Spud Year	Indicator‡	Inspected	%	Indicator‡	Inspected	%	Indicator‡	Inspected	%
2000	5	1389	0.4%	0	0	0	5	1389	0.4%
2001	10	1827	0.5%	0	0	0	10	1827	0.5%
2002	10	1564	0.6%	0	1	0	10	1565	0.6%
2003	17	1940	0.9%	0	4	0	17	1944	0.9%
2004	14	2308	0.6%	0	2	0	14	2310	0.6%
2005	22	2949	0.7%	0	6	0	22	2955	0.7%
2006	42	3307	1.3%	3	23	13.0%	45	3330	1.4%
2007	28	3461	0.8%	2	83	2.4%	30	3544	0.8%
2008	34	3337	1.0%	15	304	4.9%	49	3641	1.3%
2009	17	1620	1.0%	56	749	7.5%	73	2369	3.1%
2010	16	1345	1.2%	148	1532	9.7%	164	2877	5.7%
2011	48	1055	4.5%	107	1862	5.7%	155	2917	5.3%
2012	17	813	2.1%	24	1197	2.0%	41	2010	2.0%
SUM	280	26915	1.0%	355	5763	6.2%	635	32678	1.9%

‡ Reflects total count of indicators found in the database prior to preparation of modeled dataset. The modeled dataset requires removal of 5,223 well records to account for time dependency of the model (see methods section of main text for details).

***** Note, PADEP compliance reports indicate 8,703 wells (8,459 conventional; 244 unconventional) spudded between 2000 and 2013 have no inspections on record and are thus not included in the database or these results. Additional wells were removed from the modeled dataset due to time dependency requirements of the model (see methods for details)