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Abstract

This paper measures the effects of bankruptcy protection on industry structure and environmental outcomes in oil and gas extraction. Using administrative data from Texas, I exploit variation in an insurance requirement that reduced firms' ability to avoid liability through bankruptcy. Among small firms, the policy substantially improved environmental outcomes and reduced production. Most production was re-allocated to larger firms with better environmental records, but high-cost production where social cost may have exceeded social benefit decreased. These results suggest that incomplete internalization of environmental costs due to bankruptcy is an important determinant of industry structure and safety effort in hazardous industries.

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In almost all legal systems the debts of insolvent parties can be eliminated through bankruptcy. Bankruptcy protection improves insolvent actors' work incentives and mitigates coordination problems among creditors. However, bankruptcy protection also distorts behavior by insulating actors from worst-case outcomes. For example, financial firms may become excessively leveraged or consumers may accumulate excessive personal debt. One important implication of bankruptcy protection is that firms in hazardous industries will take excessive environmental and public health risks. Since damages can be discharged in bankruptcy, firms with assets less than their worst-case liabilities face inadequate safety incentives. Economists call this the "judgment-proof problem" (Shavell, 1986). In addition to reducing precaution in the short run, the judgment-proof problem may also distort industry structure. The ability to avoid liability through bankruptcy creates a private cost advantage for small firms, potentially shifting production away from larger producers with lower social costs of production.

This paper measures the effect of bankruptcy protection on environmental outcomes and industry composition in the onshore oil and gas industry. Motivated by stylized facts about hazardous industries, I propose a simple conceptual model of an industry with heterogeneous projects (e.g., oil wells) and firms. Bankruptcy protection lowers the expected private costs of environmental damage for small producers. As a result, small firms exercise too little care in each project; acquire some projects that would be efficiently operated by large firms; and develop additional high-cost projects where social cost exceeds social benefit.

I test the predictions of this model using data on the universe of onshore oil and gas producers in Texas. The analysis draws on several administrative databases covering production, environmental outcomes, and entry and exit. To identify the effects of the judgment-proof problem, I exploit quasi-experimental variation in insurance requirements stemming from the introduction of a surety bond mandate during 2002–2003. A surety bond is an insurance contract that obligates the insurer to pay the state for environmental costs left over if the insured firm becomes insolvent. Requiring bonds causes firms to internalize a greater share of expected environmental costs through the ongoing premiums they pay to insurers.

I find that the bond requirement caused striking changes in industry structure. About 6% of producers left the market immediately. These exiting firms were small and had poor environmental records. Among remaining firms, the bond requirement reduced production among the smallest 80% of firms by about 5% on average. Most of the oil and gas wells affected by these exits or reductions were acquired by large firms that continued operating. However, there was a reduction in very low-producing wells, where social cost (including environmental risk) may exceed social benefit.

Environmental outcomes also improved sharply. I find clear evidence of an 85% decrease in firms leaving wells unplugged at the end of production (which creates a serious risk of groundwater pollution). There were also substantial decreases in inspection violations and well blowouts coincident with the implementation of the policy. The improvements were concentrated among small firms. This group also had the highest rates of environmental incidents prior to the policy change. The results suggest that by screening out firms that insurers perceived to be high-risk, and increasing accountability for remaining firms, the bond requirement mitigated the harmful incentive effects created by bankruptcy protection.

As I discuss in Section 2, the empirical literature about the judgment-proof problem in hazardous industries is limited. This paper contributes to that literature in four ways. First, existing studies have focused on a single margin, such as accidents (Alberini and Austin, 2002) or firm size (Ringleb and Wiggins, 1990). This paper leverages project- and firm-level data on both industry composition and environmental outcomes to provide a comprehensive investigation of the judgment-proof problem in a single industry. This allows me to say more about the full impacts of limited liability than has been possible in previous studies. Second, the rich data allow for more detailed exploration of the economic mechanisms behind the observed effects. For example, I am able to track ownership of individual oil and gas leases as they transfer between firms or shut down in response to the policy change; and I am able to observe how the response to the policy change depends on a firm's past environmental compliance history.

Third, the empirical evidence in this study requires weaker identifying assumptions than previous work. Existing studies rely primarily on cross-sectional comparisons across jurisdictions, industries, or firms that are potentially vulnerable to omitted variables bias. For example, firm size may be correlated with experience or skill, which could also affect accident rates. In contrast, this paper focuses on comparisons immediately before and after a policy change, or between firms that have or have not yet been required to purchase insurance for exogenous reasons.

Finally, this study measures the significance of this market failure in one of the most important industries in the world. More than 15.3 million Americans have had an oil or gas well drilled within one mile of their home since 2000.[1] There has been a

[1]Gold, Russell and Tom McGinty. "Energy Boom Puts Wells in America's Backyards." *Wall*

great deal of empirical research on the effects of this boom (Allcott and Keniston, 2014; Darrah et al., 2014; Muehlenbachs et al., 2015). This study targets a less-widely-explored question: Do regulations induce oil and gas producers to balance profits and environmental risk appropriately? The results suggest that there would be benefits from increasing bond requirements in other oil- and gas-producing states to at least the level required in Texas, and possibly further. More broadly, they bolster concerns among economists and policymakers about limited liability problems in many sectors, including landfills, chemicals, small-scale manufacturing, and hazardous materials transportation.

The rest of the paper is organized as follows: Section 2 discusses liability and market structure. Section 3 describes the oil and gas industry. Section 4 proposes a model for how bankruptcy protection affects safety effort, firm size, and output. Section 5 describes the data and empirical strategy. Sections 6 and 7 discuss the results, and Section 8 concludes.

2 Background

Shavell (1986) proposes that individuals whose potential liability exceeds their assets will take inadequate care to prevent accidents (*e.g.*, drive their cars recklessly) and engage too often in activities that may harm others (*e.g.*, drive too much). The same reasoning applies to firms. Because safety effort is costly, firms that cannot be compelled to pay for damages will underinvest in prevention (Shavell, 2002). This problem is relevant to a wide range of industries with environmental and health risks, such as manufacturing, shipping, taxis, landfills, and retail gasoline.

Street Journal. October 25, 2013.

The judgment-proof problem also creates a private cost advantage for firms with limited asset exposure. Firms limit their liability by contracting out risky activities to small firms (Brooks, 2002), intentionally dissolving before accidents can be detected (Boyd and Ingberman, 2003), or issuing securitized debt that is senior to liability claims (Che and Spier, 2008). One obvious strategy is to stay small and limit investment. Such firms have few assets to be seized when damages occur. Existing formal models of the judgment-proof problem have had little to say about the choice of firm size or output.[2] The most similar theoretical model to the one in this paper is Van 't Veld (2006), which considers optimal firm sizes with and without liability rules (but not heterogeneity in firms or projects, or an insurance requirement).

The perceived importance of the judgment-proof problem has motivated a range of policies. One important approach is requiring firms to have liability insurance or bonds.[3] Firms comply with bond requirements either by depositing assets with the regulator until production is completed safely, or by purchasing a surety bond from an insurer. Surety bonds obligate the insurer to pay the state up to the value of the bond if the insured firm goes out of business and leaves some environmental cost.[4] Firms with few assets typically choose surety bonds instead of cash bonds.

Insurance and bond requirements mitigate the judgment-proof problem because

[2]Shavell (2002) assumes that firms produce only a single unit, and Pitchford (1995) describes firms as considering a single risky project. Ganuza and Gomez (2011) and Che and Spier (2008) assume identical output across firms while allowing for strategic choice of asset level and capital structure, respectively.

[3]Alternative policies include direct safety regulation (Shavell, 1984) and vicarious liability for lenders or business partners (Kornhauser, 1982; Pitchford, 1995; Boyd and Ingberman, 2003).

[4]Some regulators accept surety bonds (from insurers) or irrevocable letters of credit (from banks). The instruments are very similar; I follow convention among regulators and refer to both as "bonds".

firms internalize accident costs through premiums. If safety effort is fully observable, then premiums will be conditioned on it, the firm internalizes the full expected costs of accidents, and safety effort and industry structure will both be socially optimal. In the opposite extreme where safety effort is completely unobservable, the policy still has extensive-margin benefits. Safety effort is the same as before the policy,[5] and insurance premiums reflect expected damages at that sub-optimal level of safety effort. The insurance premiums screen out firms whose revenues exceed private but not social costs (i.e., production costs plus expected damages) (Polborn, 1998).

Most U.S. states require taxi firms to purchase liability insurance or surety bonds. Recently, the lack of a similar insurance requirement for transportation network companies like Uber became a public policy issue.[6] Bonds or liability insurance are also required for owners of landfills and underground chemical storage tanks, both of which can cause serious pollution problems.

Despite the prevalence and potential significance of limited liability problems, there is limited empirical evidence. Ringleb and Wiggins (1990) find that the number of small firms in dangerous industries increased during the 1970's, coincident with more aggressive enforcement of liability claims for workplace carcinogen exposure. Alberini and Austin (2002) find that in states with strong liability rules, toxics spills are concentrated among small firms. They suggest that limited liability may induce specialization by small firms in risky activities. Using state-level panel data on

[5]Shavell (2005) points out that safety effort may even decrease somewhat if insurance premiums reduce the firm's assets and thus its liability exposure.

[6]Dolan, Christopher. "Viewpoints: Uber should have enough insurance, just like anyone else". *Sacramento Bee*. August 8, 2014.

annual releases from underground storage tanks, Yin et al. (2011) finds decreased leaks in seven states after tank owners were required to purchase private liability insurance. Finally, while not focused on limited liability, a working paper by Yin et al. (2007) finds that stricter environmental regulations for underground tanks at service stations in Michigan led to increased exit by small firms.

As described in the Introduction, this paper builds on this existing literature by presenting a comprehensive picture of the judgment-proof problem in a single industry; leveraging rich project- and firm-level data to explore economic mechanisms; utilizing highly credible quasi-experimental empirical approaches; and focusing on an unstudied, highly important industry.

A separate body of empirical work examines firm size. Bain (1956) and Bloom et al. (2012) observe a wide range of firm sizes in many industries. These patterns appear inconsistent with the classic Viner (1932) model, where firm size is given by the minimum of the U-shaped long-run average cost function. Lucas (1978) posits that size differences stem from differences in scarce "managerial technology"; better-managed firms are more productive and grow larger, but span-of-control problems eventually limit the growth of all firms. In Banerjee and Duflo (2005), imperfect capital markets prevent all firms from adopting a technology with low per-unit production costs; firms with the technology grow large and others remain small.

3 The Onshore Oil and Gas Industry

There are over one million active oil and natural gas wells in the United States. These wells can produce for twenty years or more at rates that are determined by geology and decline over time. Most wells in the U.S. today are low-producing.

Seventy-nine percent of oil wells and 65% of gas wells produce less than 10 barrel-of-oil equivalents (BOE) per day; 35% of oil wells produce less than 1 BOE/day.[7]

These million wells belong to thousands of firms. Large producers with sophisticated engineering teams and production technologies specialize in fields with favorable geological conditions and thus high production rates. These large producers account for the bulk of U.S. production. Most producers, however, are small and tend to specialize in low-producing wells. During the time period examined in this study, more than 5,000 operators reported production each year in Texas alone. Appendix Table 1 shows the distribution of their annual production and revenues. The largest few firms produced billions of dollars of oil and gas per year, but most had revenues below $1 million. The 80th percentile was $1.5 million, and the 20th percentile was only $33,000. Smaller firms also tend to specialize in lower-producing, less valuable types of production. Appendix Figure 1 shows how high-producing wells are concentrated among large producers.

Regardless of their production rate, oil and gas wells pose similar risks of severe environmental contamination. Crude oil, natural gas, drilling fluids, and concentrated saltwater (an unavoidable co-product) can all seriously damage human health and natural resources. Surface leaks occur when storage tanks, waste pits, and pipes are not carefully monitored and maintained. Leaks in the cement-and-steel casing around the wellbore can contaminate groundwater, especially as the well ages or if the casing is poorly constructed. Once wells are no longer producing (or leaks

[7] All statistics are from U.S. EIA. The *Annual Energy Review 2011* (the most recent count) reports 536,000 oil wells and 504,000 gas wells. Almost all are on land. Production rates are for 2009, "United States Total Distribution of Wells by Production Rate Bracket." One BOE is one barrel of oil or 6,000 cubic feet of natural gas. One BOE represents the approximate energy content of a barrel of oil, and is a commonly used metric for combining oil and gas into a single measure.

are detected), they must be plugged with cement below groundwater depth at a cost of several thousand dollars. Firms often delay plugging; in the extreme, wells remain unplugged after the firm is dissolved. During 1983–2008, such "orphan" wells caused 17% of oil and gas groundwater contamination cases in Texas and 22% in Ohio (Kell, 2011).[8]

The presence of so many small firms complicates enforcement. According to a 2003 report by the State Review of Oil and Natural Gas Environmental Regulations, during 2001 and 2002 (before the bond requirement), Texas was unable to collect 68% of the penalties assessed for oil and gas rules violations. The most common reason these fines were uncollectible was bankruptcy.[9]

4 Model

This section presents a simple model of how bankruptcy affects hazardous industries. It extends the models discussed in Section 2 by introducing heterogeneity in firms and projects, and endogenous selection of the number of projects. The emphasis is on developing a simple model to guide the empirical analysis. I abstract away from some well-known complexities of liability regulation. For example, I assume that accidents are always detected and that penalties exactly equal damages.

The basic setup is similar to Shavell (1986) and related models. A homogeneous good is produced by risk-neutral firms in a competitive industry. Output comes from

[8] For Texas, 17% of cases came from orphan wells; 33% from production activities; 43% from waste management and disposal; and 6% from drilling and well completion. For Ohio, 22% of cases came from orphan wells; 21% from production activities; 14% from waste management and disposal; and 40% from drilling and well completion.

[9] "RRC assessed $5,183,832 in penalties and collected $1,728,595... Penalties are most often uncollectible because the company has gone out of business and has no assets" (STRONGER, 2003).

discrete projects (e.g. oil wells or factories). Each project produces a single unit of output and involves stochastic environmental costs. Firms can reduce expected environmental costs by exerting costly safety effort. The level of safety effort in each project is a continuous variable x. The price of safety effort is normalized to one, so that per-project expenditures on safety are also x. The environmental costs of each project are $h(x)$, a random variable with mean $\mu(x)$ and upper bound $\bar{h}$. Damages at each project are independent, so the firm's expected environmental costs are $\mu(x)q$. Each firm is liable to the regulator for environmental costs.

A firm chooses q and x to maximize expected profit,

$$pq - c(q) - xq - \mu(x)q \tag{1}$$

Optimal safety effort x^* minimizes effort costs plus fines (equates the marginal cost and marginal benefit of safety effort): $q[1+\mu'(x^*)] = 0$. Optimal output q^* equates marginal cost, including safety effort and fines, with price: $p = c'(q^*) + x^* + \mu(x^*)$. Firms internalize all costs, so (x^*, q^*) is also socially optimal.

Now consider an additional parameter y, which is the firm's assets that can be seized to pay fines. If y is less than damages, the difference is discharged in bankruptcy. To begin, assume y is given exogenously. Letting $f(v;q,x)$ be the probability distribution of the firm's total environmental costs v, the profit function becomes,

$$pq - c(q) - xq - \begin{cases} \mu(x)q & y \geq \bar{h}q \\ \left[\int_0^y v f(v;q,x)dv + \int_y^{\bar{h}q} y f(v;q,x)dv\right] & y < \bar{h}q \end{cases} \tag{2}$$

When y is greater than worst-case damages $\bar{h}q$, the profit function is unchanged. However, when y is less than $\bar{h}q$, the firm considers a truncated damage distribution.

Expected damages are replaced by the probability-weighted sum of damages from zero to y, plus y for all larger outcomes. The firm chooses safety effort less than x^* because it does not fully internalize damage outcomes greater than y.

The Judgment Proof Problem With Heterogeneous Firms

Motivated by the oil and gas industry structure described in Section 3, this section presents a simple conceptual model of a hazardous industry with heterogeneous firms and projects. Potential projects (*e.g.*, oil well sites or factory locations) vary in an exogenous characteristic λ related to production cost (such as the quality of the underlying oil and gas resource). More favorable sites have larger λ.

Firms specialize in one of two technologies. In both cases, the production function depends on λ and a composite mix of other inputs L. The advanced technology involves strong complementarities in λ and L, so that it achieves low marginal costs at favorable sites. At less favorable sites, the advanced technology is less suitable and a low-technology approach achieves the same or lower marginal cost.[10] Thus, both types of firms are present in equilibrium. High-technology firms operate projects at favorable sites and grow large due to the complementarities between λ and investment.[11] I refer to "large" and "high-technology" firms interchangeably, and similarly for "small" and "low-technology."

The marginal costs of producing a project (not including safety effort or environmental costs) for high- and low-technology firms are $c^H(\lambda)$ and $c^L(\lambda)$, both of

[10] In oil and gas, advanced techniques like directional drilling or enhanced oil recovery require large investments and achieve low per-unit costs in fields with rich reserves. In depleted or marginal-quality fields, these techniques have little or no advantage over low-technology methods (e.g., pumpjacks).

[11] If there are fixed costs of investment in the advanced technology, this creates an additional reason for high-technology firms to be large.

which are decreasing in λ. The cost of safety effort and the distribution of damages are the same for both types.[12]

Figure 1 depicts the market graphically. The horizontal axis shows potential projects ordered from highest to lowest λ (i.e., the most favorable sites are on the left side of the axis). The exogenously-given world price is p. The thick solid lines show aggregate marginal cost curves for large- and small-type firms when they are fully accountable for environmental damages. The steepest solid line is the large type's marginal cost, including optimal safety effort and fines: $c^H(\lambda) + x^* + \mu(x^*)$. The other thick line is the small type's marginal cost: $c^L(\lambda) + x^* + \mu(x^*)$. Because both types are fully accountable, only production costs differ. Thus, all projects to the left of $\hat{\lambda}^*$ are produced by large-type firms. Projects between $\hat{\lambda}^*$ and $\underline{\lambda}^*$ are produced by low-technology firms. Potential projects to the right of $\underline{\lambda}^*$ are not produced.

Bankruptcy Distorts Industry Composition

Large firms have many valuable projects. If damages from one project exceed that project's value, the regulator can seize value associated with other projects.[13] Thus, large firms are less likely to experience damages that exceed the value of the firm's assets.[14] For simplicity, in the following discussion I assume large firms are large enough to fully internalize potential environmental costs.

[12] In onshore oil and gas, potential damages are likely similar across wells. A more complex model could allow economies of scale in x. This would reinforce the result that large firms take more care.

[13] Technically, this argument assumes that the value of each high-technology project is at least as large as expected per-project damages. When high-technology projects are valuable and accidents are rare, this assumption is not restrictive.

[14] There are additional reasons that small firms are more likely to be judgment-proof. Long-lived hazards like carcinogen exposure and some types of water pollution may take years to manifest. The probability that small firms will still exist by then may be lower (Ringleb and Wiggins, 1990; Davis, 2015). Boyd and Ingberman (2003) argue that small firms can more easily "fly-by-night", quickly liquidating in anticipation of liability claims.

The ability to avoid environmental costs through bankruptcy lowers the expected private costs of small firms. The dashed line in Figure 1 shows marginal private costs for small firms when damages are dischargeable in bankruptcy,

$$c^L(\lambda) + x^\circ + z(x^\circ) \tag{3}$$

Safety effort x° is less than socially-optimal safety effort x^*. Expected fines are $z(x^\circ)$, which is less than $\mu(x^\circ)$.[15] On the other hand, the judgment-proof problem *increases* social marginal cost to $c^L(\lambda) + x^\circ + \mu(x^\circ)$, the top-most light gray line. This occurs because the social cost of safety effort and expected damages is $x^\circ + \mu(x^\circ) > x^* + \mu(x^*)$, since x^* minimizes $x + \mu(x)$ by definition.

The three areas labeled A, B, and C represent welfare losses from the judgment-proof problem. Area A represents increased environmental damages. Because small firms exert less than the socially-optimal level of safety effort, environmental damages are higher than would be efficient. Area B represents production inefficiencies. The artificially low private costs of small firms lead them to produce projects between λ^0 and λ^*, which would be more efficiently operated by large firms. Finally, area C represents overproduction. Judgment-proof firms produce projects from $\underline{\lambda}^*$ to $\underline{\lambda}^0$, where marginal social cost exceeds marginal social benefit (p).

The final two sections of the model are described in Appendix 2. They describe how an insurance requirement mitigates the judgment-proof problem and briefly discuss capital structure and other issues.

[15] From Equation 2, $z(x) = \frac{d}{dq}[\int_0^y v f(v;q,x)dv + \int_y^{\bar{h}q} y f(v;q,x)dv]$. To see that $z(x) < \mu(x)$ note that an additional project creates equal fines for both firms if total damages are less than or equal to y, and lower fines for the judgment proof firm if total damages exceed y.

Testable Predictions

This model makes several predictions about policy changes that reduce the ability to avoid liability through bankruptcy.

- Environmental outcomes will improve. Small firms will have large improvements.
- Small firms will reduce the number of projects that they operate:
  - Output will be re-allocated from small to large firms as $\hat{\lambda}$ moves towards $\hat{\lambda}^*$.
  - High-cost projects will shut down as $\underline{\lambda}$ moves towards $\underline{\lambda^*}$.
- Small producers that are not profitable after internalizing environmental costs will exit. Exiting firms will have had poorer environmental records on average.

5 Empirical Setting and Data

The empirical analysis focuses on onshore oil and gas extraction in Texas. This is an excellent setting for studying liability and bankruptcy. There are major environmental risks and many small producers. Firms produce homogeneous products and the industry is essentially perfectly competitive due to extremely liquid international markets (in which Texas is a small share of total production). Lastly, the size of the industry means that rare environmental incidents are observed frequently enough to allow meaningful empirical analysis.

Credibly measuring the effects of the judgment-proof problem requires variation in firms' ability to avoid liability that is uncorrelated with unobserved determinants of the outcomes of interest. This is a difficult empirical challenge. For example, comparisons across jurisdictions with varying liability regimes may be biased if firms that anticipate having accidents locate in areas with weak liability rules. Similarly, deep-pocketed firms may also be more experienced or skilled than financially-weak producers, making their operations safer. This paper solves this identification problem by exploiting variation in bond requirements. Stricter bond requirements reduce small firms' ability to escape environmental costs. Texas implemented a universal bond requirement for oil and gas producers during 2002–2003. This requirement became binding on firms at the time of their first annual operating license renewal after the change. License renewal dates depend on the anniversary of the firm's creation, creating a quasi-random rollout. As I describe in Section 6, I use this variation in different ways to separate the effects of the policy change from other time-varying determinants of industry composition and output.

Bond requirements for oil and gas companies were first introduced by the Texas Legislature in 1991, but only for some producers. Firms with an acceptable compliance history could instead pay a $100 annual fee called the "Good Guy Fee."[16] This option was chosen in 76% of license renewals during 1992–2001. In 2001, Senate Bill 310 extended the bond requirement to all oil and gas producers, eliminating the Good Guy Fee. This rule passed the legislature in June, 2001 and took effect in March, 2002. I focus the analysis primarily on the universal bond requirement because prior to this, few firms were bonded.[17]

The bond amount depended on the number and depth of wells. The formula was

[16]Firms with a four-year record of compliance with Commission regulations could pay the Good Guy Fee. Firms ineligible for the Good Guy Fee could also avoid bonding through an annual cash fee equal to 3% of the required bond amount. For unbonded operators, the law also introduced a $100 annual fee for each inactive, unplugged well.

[17]Senate Bill 310 also allowed one final non-bond alternative, a sharply elevated annual fee equal to 12.5% of the required bond amount, to persist as a temporary alternative until 2004.

$2 per foot of well depth across all wells. The mean depth of existing wells in 2001 was 3,300 feet.[18] Alternatively, producers could cover a number of wells with a "blanket bond." Up to 10 wells could be covered with a $25,000 blanket bond; 11 to 99 wells with a $50,000 blanket bond; and over 100 wells with a $250,000 blanket bond.[19]

Ninety-seven percent of bonded producers chose to purchase a bond from an insurer instead of posting their own assets as a cash bond.[20] The annual premium for a surety bond is typically 1-2.5% of the face value of the bond. However, for firms that are deemed to be high-risk because they are financially weak or have a poor safety record, premiums can exceed 10-15%. Insurers may also require collateral from high-risk firms (Gerard, 2000; Boyd, 2002; Kaiser and Snyder, 2009; Gerard and Wilson, 2009). Thus, the primary effect of the bond requirement was to substantially increase the operating costs of firms for which the market perceived a high risk of insolvency and environmental damage. A low-risk operator with three wells might pay $400 per year in bond premiums, while a high-risk operator with the same number of wells might pay $3,000 per year while also facing collateral requirements.[21]

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[18] This is the total depth of wells operated in 2001 divided by the number of wells.

[19] Between steps in the blanket bond schedule, the marginal increase in the required coverage level is zero. It is worth considering whether this introduced new economies of scale. In practice, any effect was likely small. First, adding wells increased the surety's risk exposure and so should have increased premiums for a given level of coverage. Second, bond costs were small for low-risk firms. A large firm acquiring a low-risk three-well firm could have saved about $200 per year for each firm, following the example calculation on the next page. These savings were likely small compared to other benefits and costs of merging. For high-risk firms, the benefits of combining with a producer with a good reputation were higher. But this is not due to the blanket bond – it is due to the acquiring firm being a better insurance risk, and thus paying smaller premiums.

[20] 97% of bonded license renewals from 2002-2005 used surety bonds or letters of credit.

[21] Low risk firm: 3 wells * 3,300 ft. * $2/ft. * 2%. High-risk: 3 wells * 3,300 ft. * $2/ft. * 15%.

The importance of the bond requirement to producers was reflected in the news coverage it received. Bonding was controversial because of a perception that it pushed out small firms. An op-ed in the *Midland Reporter Telegram* stated, “Bonding is no problem for major oil companies and large publicly owned independent companies. The small independent, however, is finding bonding very difficult at best... If the Railroad Commission persists in its current bonding requirements it could put thousands of honest hardworking Mom and Pop operators out of business.”[22] Under the headline, “Can’t Afford the Bond? Then Don’t Run a Well,” the *San Antonio Express News* editorialized, “Texas is better off if only companies that can afford to be responsible environmental stewards stay in the oil and gas business.”[23]

The required bonds were conditioned on preventing all types of water pollution. The bond contract states that “all oil and gas activities and operations shall be carried out so as to prevent pollution of any ground or surface water in the state.”[24] Unlike liability insurance, if the state makes a claim against the bond, the insurer will seek repayment from the oil and gas producer. Thus, these bonds transfer default risk from the state to the insurer.

5.1 Data

I construct a novel dataset on market structure and environmental outcomes by merging several administrative databases from the Railroad Commission of Texas (RRC), the state agency that regulates oil and gas production. Appendix 3 describes the creation of the dataset in detail. The final merged dataset includes 257,318 leases

[22]“PBPA members detailing problems getting bonds.” *Midland Reporter Telegram*, Mar. 31, 2002.

[23]“Can’t Afford the Bond? Then Don’t Run a Well.” *San Antonio Express News*. Aug. 9, 2002.

[24]Railroad Commission of Texas Blanket Performance Bond Form P-5PB(2).

with at least one month of non-zero production during 1993–2012, and 35,568,267 lease-month observations. A lease is a parcel of land on which the producer has negotiated production rights, and includes one or more wells. Each lease-month observation belongs to one of 10,489 producers.[25] I observe the entry and exit dates for these producers based on their annual license applications. I define entry as the date of first application, and exit as 12 months after the final license renewal.

Orphan well data come from the Railroad Commission's March, 2014 Orphan Well List. It includes 6,314 wells with no existing operator and no production. For environmental rules violations, I focus on field inspection violations related to Statewide Rules 8 and 14. Statewide Rule 8 ("Water Protection") governs water quality protection during drilling and production. Statewide Rule 14 ("Plugging") requires that inactive wells be plugged properly and promptly.[26] There are 6,972 violations of Rule 8 and 5,318 violations of Rule 14 in the final dataset. The dataset also includes 522 well blowouts since 1990. Operators are required to notify the Commission when blowouts occur. Orphan wells and rules violations are merged to operators using operator identification numbers. The blowout data do not include these numbers for all observations. I perform a careful "fuzzy" merge based on lease names and numbers, but I emphasize aggregate instead of firm-level outcomes for blowouts.

[25] The RRC identifies some operators as having related ownership (for example, name changes). In a robustness check in Appendix 1.1, I collapse related operators into 9,888 firm groups and reproduce the main results.

[26] I focus on these rules to exclude minor procedural violations, such as paperwork delays or improper signage. Examples of violations include, "Well #3 Inactive/Unplugged. Well #2 open to atmosphere. Required signs not posted. Oil on ground inside and outside of firewall"; "Oil/oil saturated soil at well not cleaned up/remediated. Well inactive/unplugged. Vegetation on firewall a fire hazard"; and "Post signs; disk,turn or till oil saturated soil; equip well #1 w/ appr'd wellhead assembly; install a bradenhead observ valve."

5.2 Descriptive Evidence of High Incident Rates for Small Firms

Even before considering the empirical results, the raw data on incident rates suggest the possible importance of the judgment-proof problem. Figure 2 shows that environmental incidents were concentrated among small operators. I calculate average annual production for each operator during 1993–2001. The horizontal axis shows the sum of annual production across all firms. Operators are ordered along this axis from smallest to largest annual production so that, for example, 0.2 represents the 20% of output that comes from the smallest firms. The vertical axis shows the cumulative share of environmental incidents. The dashed gray line has a slope of one. Almost 100% of orphan wells, 95% of field rules violations, and 40% of blowouts are associated with the 20% of production that comes from the smallest firms.

6 Results

6.1 Industry Composition

The theory predicts that the bond requirement will re-allocate projects from small to large firms, and potentially cause small producers to exit if they are not profitable after incorporating environmental costs.

Effect of the Policy on the Rate of Exit

Figure 3 shows the raw data on exit. The dots represent the number of firms leaving the market each month. Prior to the introduction of the partial bond requirement in September 1991, about 40–50 firms exited each month. With the bond requirement, exit increases sharply to over 100 firms per month and stays high for 12 months, then decreases sharply. The same pattern accompanies implementation of the universal bond mandate. In March 2002, exit almost doubles from about 60 to over 100 firms per month.[27]

I measure this exit effect using a regression discontinuity design that compares the exit rate immediately before and after implementation of the policy. I observe each firm once per year in its assigned renewal month. The estimating equation is,

$$1[Exit]_{it} = \alpha + \beta_1 1[Begin\ Rollout]_t + \beta_2 1[End\ Rollout]_t + \beta_3 T_t + X_t \beta_4 + \eta_{it} \quad (4)$$

The dependent variable $1[Exit]_{it}$ is an indicator variable equal to one if firm i leaves the industry in month t. After firms exit they are removed from the sample. $1[Begin\ Rollout]_t$ is an indicator variable equal to one in March 2002 and all later months. $1[End\ Rollout]_t$ is an indicator variable equal to one in March 2003 and all later months. T_t is a flexible polynomial in the running variable, month. X_t includes monthly crude oil prices and month-of-year fixed effects.[28] Controlling for output prices and month of year improves precision and allows comparison of the effect of the policy to the effects of short-term fluctuations in prices. The constant term α gives the background level of exit prior to the policy change. T_t and output price are centered at their March, 2002 values, so α gives the level of exit immediately prior to the policy change.

In my preferred specification, I include 48 months before March, 2002 and after February, 2003. Appendix Table 4 shows results for other bandwidths. Following Lee and Card (2008), I cluster the standard errors according to the running variable. The running variable is month; I cluster by quarter to allow for arbitrary correlation of error terms across firms and months in each quarter.

[27] Appendix Figure 4 shows entry and net entry (entry minus exit).

[28] Crude oil and natural gas prices are highly correlated during this period (correlation coefficient 0.8). To simplify interpretation of the price effects, I include oil prices only.

The error term η_{it} includes unobserved determinants of $1[Exit]_{it}$. The identifying assumption is that η_{it} does not change discontinuously at implementation. In that case, β_1 cleanly measures the effect of the policy introduction on exit. This assumption is supported by the similar 12-month patterns of exit observed for the 1991 and 2002 policies. There are clear discontinuous increases in exit during each period, suggesting that the effect in 2002 is unlikely to be caused by an unobserved idiosyncratic shock. The timing of both rollouts differs (one starts in September, the other in March) and both split calendar years.

Appendix Figure 9 shows the number of firms up for license renewal each month. Renewal dates are assigned by the RRC and cannot be changed by firms. The bond requirement was implemented according to assigned renewal dates; firms could not avoid it by submitting their renewal paperwork early. As expected, the number of firms up for renewal is smooth across the implementation threshold.

Figure 4 shows a graphical version of the regression in Equation 4. The horizontal axis shows months before and after March 2002. The dots are monthly means of the residuals from a regression of $1[Exit]_{it}$ on a constant term, month-of-year fixed effects, and monthly oil prices. The fitted curves are a quadratic polynomial for the pre-period, a separate linear fit for the implementation year, and a separate quadratic polynomial for the post-period. There is a clear increase of about six percentage points in the share of firms exiting in March, 2002. At the end of the implementation period, there is a decrease in exit to approximately pre-implementation levels.

Exit is lower during the last three months of the implementation period (Dec. 2002–Feb. 2003), creating a negative slope in the fitted polynomial. During these three months, a legal challenge temporarily limited full enforcement of the policy for firms that had not already renewed their licenses.[29] Appendix Figure 2 shows this same figure excluding the final three months of the implementation year. The fitted trend in exit during implementation is substantially less steep.

Figure 5 shows the effect by quintile of firm-level average annual oil and gas production. These quintiles are defined based on average production during 1997–2007 in barrel of oil equivalents (BOE), and are listed in Appendix Table 1.[30] The effect of the bond requirement is largest for small firms. Among the smallest 20% of producers, there is a clear increase in exit of about 15 percentage points in March 2002. In the second quintile, the effect is about 10%; in the third, it is about 7%, and in the fourth it is about 2%. In each of these middle quintiles the effect is growing smaller, but is clearly visually distinguishable. In contrast, in the top quintile of firm size there is no distinguishable change in the share of firms exiting in March 2002.

Table 1 shows regression results for equation 4. As in Figure 4, each specification includes a quadratic polynomial in time for the four years before the policy; a separate linear polynomial for March 2002–February 2003; and a separate quadratic polynomial for the following four years. In Column (1), the implementation of the expanded bonding rule causes a discontinuous increase in exit of 6.0 percentage

[29] On November 27, 2002 a Travis County Court judge issued a temporary restraining order requiring the Railroad Commission to accept $1,000 cash payments in lieu of bond coverage from operators who qualified for the ”Good Guy” exemption. The bond requirement was eventually upheld, but producers who came up for renewal during this period may have stayed in the market another year in hopes of the rule being overturned.

[30] Results are similar if I use value of production instead of BOE; however, BOE is my preferred metric of output because the measure is not affected by price changes over time. Throughout the paper, I use the quintile cutoffs shown in Table 1.

points. This means that an additional 6% of the firms scheduled to renew their license each month chose to leave. The baseline rate of exit before the policy change, given by the constant term, is 10.1%. The specification in Column (2) controls for crude oil prices in each firm's assigned renewal month. This increases the estimated effect of the bond policy slightly to 6.2 percentage points. The effects of price increases on exit are negative, as expected. Finally, the specification in Column (3) also includes month-of-year fixed effects. Including the fixed effects has little effect on the estimates, which suggests that there are not important systematic differences in firms across assigned license renewal months.

Table 2 presents regression results according to firm size. The results are consistent with the graphical evidence in Figure 5. The specification in each column matches Column (3) in Table 1. In the first and second quintiles exit increases by 12.7% and 11.0%, while in the third and fourth quintiles it increases by 6.9% and 1.9%. There is no effect of the policy change on exit for firms in the largest output quintile. The background level of exit also decreases across quintiles, from 17.4% to 6.7%.

Firms with poor environmental records were predicted to face higher premiums and thus be more likely to exit due to the insurance requirement. Appendix Table 2 shows the relationship between exit during the implementation period and compliance history during the previous 10 years. Panel A shows a negative binomial regression of the count of past water protection rules violations on an indicator variable for exit during March 2002 – February 2003. Column (1) includes all firms in the industry immediately prior to the requirement. Exiting firms have 35% more violations than firms that stay. Columns (2) and (3) limit the sample to firms with a small number of leases. Even when limiting the sample to these small firms, exiting firms have 22% –39% more violations. Panel B shows OLS estimates for robustness. The estimated differences in violations are similar, but the precision is poor due to the count nature of the data.

Ownership of Oil and Gas Leases

The model predicts a reallocation of projects where the judgment-proof problem created an artificial advantage for small firms. I evaluate this prediction by testing for an abnormally high rate of ownership transfers of oil and gas leases to large firms coincident with the implementation of the policy.

Table 3 compares the share of leases sold during March 2002–February 2003 to the three years before and three years after. Panel A shows that the overall transfer rate during implementation was slightly higher (0.86 percentage points) than in surrounding years, mostly due to transfers where the buying firm had more leases than the selling firm. Panel B restricts the sample to leases initially owned by the the smallest 80% of firms. Here, the transfer rate was much higher in the implementation year (3.13 percentage points, or about a 30% increase). The difference is almost entirely accounted for by transfers to larger firms. This year-to-year comparison is imperfect, since other time-varying shocks would also have affected lease transfer rates. However, the unusually large number of transfers from small to large firms during the implementation period is consistent with a reallocation of projects in response to the policy.

6.2 Oil and Gas Production

The theory predicts that the judgment-proof problem increases output from small firms, and that the bond requirement will thus reduce small-firm output. I measure the effect of the policy on firm-level oil and gas production by comparing firms that have already purchased a bond to firms that have not yet had to purchase a bond. This design leverages the panel nature of the monthly production data through firm and time fixed effects, which reduce noise and allow me to separate the effect of the bond requirement from other time-varying factors like oil and gas prices.

I run the following regression,

$$ln(Production_{it}) = \gamma + \psi 1[Bonded]_{it} + \delta_i + \tau_t + \nu_{it} \tag{5}$$

The sample is limited to the 12 months during the implementation year, and to firms that stayed in the industry after the bond mandate. $Production_{it}$ is firm i's production (in barrel-of-oil equivalents) in month t. $1[Bonded]_{it}$ is an indicator variable equal to one for firm-month observations after the license renewal date. δ_i is a firm fixed effect, and τ_t is a month fixed effect. In my preferred specification, I interact $1[Bonded]_{it}$ and the month fixed effects with a categorical variable for firm size quintile. This estimates the effect of bonding separately for each size group, and allows for separate arbitrary time trends in production within each output quintile.

The identifying assumption in this analysis is that ν_{it} is independent of $1[Bonded]_{it}$, conditional on δ_i and τ_t. As explained previously, $1[Bonded]_{it}$ is entirely determined by the firm's assigned license renewal date and these dates are not manipulable by firms. As a further check on this assumption, Appendix Table 5 compares the average output and number of leases across renewal month groups. There does not seem to be any evidence of differences across groups.

Table 4 shows the effect of bonding on production for firms that became bonded.

Column (1) is a regression of logged monthly production on $1[Bonded]_{it}$, with firm fixed effects. In this specification, production decreases by 6.7% on average after firms become bonded. Column (2) adds month-by-output quintile fixed effects to control for variation over time in other determinants of oil and gas production, such as output prices. These time fixed effects reduce the estimated effect to 3.5%. Column (3) estimates separate effects for firms above and below the 80th percentile of firm size. Small firms reduce their production by about 4.7%, while the point estimate for large firms is near zero. Finally, Column (4) estimates separate effects for each quintile. There is a clear decreasing pattern with size. The largest estimated effects are in the bottom three quintiles: 9.5%, 6.3%, and 5.3%.

Appendix Table 6 shows a robustness check using data from surrounding years. If production were affected by some feature of license renewal other than the bond rollout, or if systematic differences between renewal month groups introduced correlation between $1[Bonded]_{it}$ and unobserved determinants of production, one would expect similar results in other years. There is no statistically significant effect of license renewal on output in this placebo analysis.

Since well-level production rates are primarily determined by geology and not operator decisions (Anderson et al., 2014), these decreases in firm-level production are likely due to firms operating fewer wells after becoming bonded. I pursue this topic further in the following section.

Lease-level production changes

The theory predicts two channels for the decrease in small-firm output. The first is reallocation of projects to large firms, which was explored at the end of Section

6.1. The second is a reduction in projects where social marginal cost exceeds social marginal benefit. I use lease-level production rate as a rough proxy for marginal cost to explore this channel. As discussed in Section 3, production rate is determined largely by geology and is thus a rough proxy for λ in the theoretical model. Low-producing wells have high per-barrel costs, including environmental costs. As much as 98% or more of the production from these wells may be saltwater, which is costly to manage safely. They are also often old and thus at higher risk of leaks. Finally, site reclamation costs are high relative to the value of production.

Prior to the bond requirement, some small producers acquired multiple low-producing wells with high expected plugging costs, presumably expecting to avoid reclamation costs. These producers found it difficult to purchase bonds after the policy, prompting Railroad Commissioner Michael Williams to write, "Their problem stems from their own bad choices... They acquired large numbers of low producing wells that will generate insufficient revenue to pay the cost of plugging when it becomes necessary to do so. They made no plans to handle future environmental problems... Their actions threaten the health of Texas waters and even the future viability of their very own oil and gas operations."[31]

Figure 6 shows the number of active leases by month and production rate bin. For ease of comparison, the data are normalized relative to eighteen months before the policy. The smallest bin includes leases reporting greater than zero but fewer than five barrels (BOE) per month. Immediately prior to the bond requirement this bin included 2,928 leases, or about 2.6% of all active leases. There is a decrease in

[31] "Williams Continues to Support RRC Bonding Program," Texas Railroad Commission press release, January 27, 2003.

these lowest-producing leases during and after the implementation of the bond requirement, consistent with producers shutting them down or declining to acquire new low-producing leases. The number of higher-producing leases, in contrast, is slightly increasing. Notably, oil and natural gas prices were generally increasing during this period (as shown in Appendix Figure 10), making it unlikely that the decrease in low-producing leases is a pure price response. If one takes the observed decrease in the smallest bin between February 2002 and February 2004 literally as the effect of the policy, the insurance requirement led to the shutdown of 429 of the lowest-producing leases in the state over two years. This comparison is imperfect because of other time-varying factors affecting production, and because lease-level production rate is not a perfect proxy for production cost. Nonetheless, it provides suggestive evidence of one channel for the production decrease among small firms.

6.3 Environmental Outcomes

Abandoned Wells

Non-producing wells that are not plugged with cement create a serious risk of groundwater contamination. The extreme version of this problem is "orphan" wells – wells left unplugged by firms that no longer exist. From an empirical perspective, orphan wells are an attractive measure of environmental effort because the regulator observes them all. There is no concern about underreporting by firms or discretion in monitoring effort.[32] Reducing orphan wells was also a primary motivation of the

[32] Operators must notify the Railroad Commission and submit certification of plugging by an RRC-approved cementing company when each well is plugged. Non-producing wells are observable as unplugged wells that are not reporting production; orphan wells are those where the operator is also no longer registered.

bond requirement, so this outcome is of independent policy interest.

Figure 7 shows the rate of well orphaning over time. The dots represent the average number of orphaned wells per lease among firms exiting each month. The dashed vertical line shows March 2003, the month after the end of the implementation period. This is the first month in which exiting firms would have been bonded under the policy (as of this month, all firms would have renewed their annual license since the requirement took effect). The horizontal gray lines show three-year averages before and after. Before bonding, exiting operators left behind 0.08 orphan wells per lease. After, the average is about 0.02, and in many months the exiting operators leave no orphan wells. Appendix Figure 5 shows the share of operators leaving any orphan wells and the total number of orphan wells by month. In all of these measures, there is a clear, large fall in well orphaning exactly coincident with the bond requirement.

The theory predicts that these improvements should be concentrated among small firms. Table 5 shows regression estimates of the change in well orphaning. The first column includes all firms, and the next five show separate regressions by size quintile. The dependent variable is orphan wells per lease at the firm level. There is one observation per firm, in its exit month. Each regression also includes a quadratic polynomial in month of exit. The constant terms in each column show that small firms had much higher rates of well orphaning prior to the bond requirement. The point estimate for quintile one is more than 14 times larger than for quintile five. The decrease in well orphaning among small firms is also striking. $1[Bonded]$ is an indicator variable for firms that exited in or after March, 2003. The percentage reduction in well orphaning was close to 100% in each of the smallest three size groups. In the two largest groups, where the amount of orphaning was already small, estimated reductions were small and not statistically significant. Appendix Figure 6 shows this same result graphically.

The economic mechanism behind this effect was likely risk selection and monitoring by insurers. After the policy change, all firms still in the industry had been judged to be acceptable risks by some insurer, based on their financial position and compliance history. In addition, insurers are able to monitor firms' assets, production, and environmental liabilities over time. If the firm accumulates many non-producing wells or its net assets begin to decrease, the insurer can raise premiums. This prevents firms from accumulating unsustainable plugging or other environmental costs over time and eventually declaring bankruptcy. In an interview, an insurer active in this market described exactly this type of monitoring.

Other Environmental Outcomes

Figure 8 shows water protection rules violations by month. Firms have an incentive to reduce violations as soon as they know that they will have to purchase insurance, because they expect insurers to price the firm's compliance history into premiums.[33] Thus, I consider the date at which the rule passed the Texas Legislature as the onset date for the policy. The vertical dashed line shows the bill's passage in June, 2001. Again, the horizontal gray lines show the mean number of violations during three years before and after the policy change. The number of violations after the policy change is lower, and there is a noticeable discrete fall in violations at June 2001. Appendix Figure 7 shows that these decreases are largest among small firms.

[33] In contrast, the decision to leave orphan wells accompanies the decision to leave the industry, so future reputation is less of a concern.

Figure 9 shows well blowouts. Because blowouts occur most frequently during drilling, I normalize the number of blowouts by the number of active drilling rigs.[34] The vertical line represents the policy's passage and the horizontal lines represent five-year averages before and after. Before 2001, the time series of blowouts is noisy but relatively flat. There is a sharp drop coincident with passage of the bond requirement, and then the blowout rate remains low.

Appendix Table 3 shows regression estimates of the changes in rules violations and blowouts. Because these are count data, I use negative binomial regression.[35] The dependent variable in Columns (1) and (2) is the count of rules violations each month. This is normalized by the number of wells operated by the firm. Column (1) shows that a before/after comparison estimates a 13% decrease in the frequency of rules violations per well after the policy change. In Column (2), including an exponential time trend and month-of-year fixed effects increases the estimate slightly, but decreases its statistical significance. Columns (3) and (4) address well blowouts. In these regressions the count of well blowouts in each month is normalized by the number of active drilling permits held by the firm in that month. There is a 40% decrease in blowouts in the before/after comparison, and a 72% decrease after controlling for an exponential time trend and month-of-year fixed effects.

This time series evidence for rules violations and blowouts is suggestive, but it does not rule out causes other than the bond requirement. Because these events are rare, it is difficult to overcome this limitation as effectively as for outcomes like exit and production. However, it is possible to look for obvious alternative

[34]Data on the number of active rigs each month come from the Baker Hughes Historical Rig Count dataset, http://www.bakerhughes.com/rig-count.

[35]Results are similar for poisson and negative binomial models.

explanations. As one simple robustness check, Appendix Figure 8 shows onshore blowouts in Louisiana, a nearby state.[36] If blowout rates in Louisiana also changed in 2001, that would suggest a national-scale shock. Perhaps due to lower production, the Louisiana data are noisy during the pre-period. There are more quarters with many blowouts, but also more quarters with no blowouts. There may also be a smooth downward trend over time. However, there is no obvious discrete change in blowouts in 2001 like there is for Texas.

To consider the possible role of other Texas policy changes, Appendix Table 7 shows all rules that were implemented or amended by the RRC in 2001 and 2002. The first column shows the date that the proposed action was published for public comment in the Texas Register. The second column shows the date that the regulation took effect. The other RRC actions were primarily procedural, and it seems unlikely that any of them would have caused the observed changes in environmental outcomes.

7 Discussion

The empirical results are consistent with greater internalization of environmental costs, as predicted by theory. Prior to the policy change, small, financially weak operators could produce oil and gas at low private cost by avoiding environmental costs through bankruptcy. Bonding mitigated this problem. Firms with high expected environmental costs, as judged by insurers, faced high bond premiums.

[36] Louisiana blowout data are from the Louisiana Department of Natural Resources SONRIS database: http://www.sonris.com/dataaccess.asp. To focus on onshore production, I include all blowouts at wells with a valid Public Lands Survey System "Township" designation. The number of active drilling rigs each month comes from the Baker Hughes Historical Rig Count dataset (http://www.bakerhughes.com/rig-count). I include rig activity for "land" and "inland water" areas.

Previously judgment-proof firms either became bonded and produced less output with greater safety effort, or they left the industry. These changes re-allocated wells from small to large producers and reduced the number of high-cost projects where social cost is likely to exceed social benefit. Bonding also caused striking reductions in abandoned wells, and there is suggestive evidence of other environmental improvements.

7.1 Alternative Explanations

Another candidate explanation for some of the results is that inefficiencies in the surety bond market increased small firms' costs for reasons unrelated to environmental risk. Such inefficiencies could include market power among insurers, credit constraints, or transaction costs. Gerard and Wilson (2009) report that many insurers and banks offered bonds, so it is unlikely that insurer market power raised prices. Credit constraints are less binding in surety bond programs than under cash bond requirements, where firms must post their own assets. In principle it is still possible that the annual premiums on the surety bond could have exacerbated liquidity constraints. However, the empirical results are not consistent with credit constraints being the sole or primary force at work. The scale of environmental improvements observed, particularly for small firms, strongly suggests that premiums were tied to environmental risk instead of indiscriminately punishing small or liquidity-constrained firms. In addition, even after conditioning on firm size, firms that exited in response to the bond requirement had poorer environmental records. This is again consistent with insurers pricing environmental risk. Insurers can observe firms' production and environmental compliance histories through the Railroad Commission, and also review balance sheets, credit scores, and other financial indicators.

As discussed in the Model Appendix, when required bond amounts are large, transaction costs such as underwriting expenses can prevent participation by firms that would operate responsibly. In this case, however, the required coverage amounts were much less than the worst-case damages from a ground- or surface water contamination event. In addition, underwriting and other transaction costs seem unlikely to explain the reported pattern of bond prices, with typical prices only 1-3% of the bond amount but a small share of firms receiving very high bond price offers.

Finally, from a welfare perspective, the importance of potential inefficiencies in the surety market is limited because output was primarily re-allocated, not reduced. Of the leases operated by exiting firms, 94% continued to produce for other firms.[37] There is no reason to think the exiting firms had systematically lower costs.

7.2 Welfare Effects of the Judgment-Proof Problem

This section relates the empirical results to the theoretical framework. Some caveats are required. The bond mandate did not completely eliminate the judgment-proof problem because required bond amounts were less than worst-case damages. Thus, these estimates represent lower bounds on the effects of limited liability. This study also does not measure every parameter needed for the full welfare calculation. Finally, some of the estimates (like the number of high-cost wells eliminated) are rough approximations. Still, tying the results to the model illustrates how the effects on different margins combine to create substantial overall welfare impacts.

[37] As expected, the 6% that shut down were disproportionately low-producing. Their median monthly production was 50 BOE, compared to 400 for those that continued operating.

In Figure 1, Region B represents efficiency losses when projects are misallocated to small firms. The re-allocation of leases after the policy change suggests that the width of B, which is the number of projects misallocated, was about 3% of the leases operated by small firms, or 744 leases.[38] Region C represents projects where marginal social benefit is below marginal social cost, even if safety effort were optimal. If the decrease in lowest-producing leases is taken literally as the policy effect, the width of C was about 429 leases. A full welfare calculation would also require the heights of B and C. For example, the height of B is the production cost difference between small and large firms ($c^L - c^H$).

Region A represents excessive environmental risk. Each project produced by a judgment-proof firm causes more environmental damage (in expectation) but also requires less safety effort than if the firm were fully accountable. The height of A is the net of these effects: $\mu(x^\circ) - \mu(x^*) - (x^* - x^\circ)$. This study measures large improvements in environmental outcomes. The clearest effect is a near 100% decrease in well orphaning among small firms.[39] These improvements required greater safety effort. As long as penalties were set at or below true damages, profit maximization implies that the net of environmental benefits and effort costs is positive.[40]

Other market failures may also be relevant. If small firms provide positive external benefits such as technology development, it may be efficient to encourage small firms. However, exempting firms from accountability for environmental damages is

[38] Table 3, Panel B: Transfers to larger firms were 3.04 percentage points above adjacent years.

[39] Measuring the economic value of these improvements is difficult. The average cost of a contaminated groundwater site is $11.4 million dollars; the average cost of a leaking underground storage tank is $125,000 (National Research Council, 2013). The average cost to remediate a Superfund site is $43 million (Greenstone and Gallagher, 2008).

[40] In practice, expected fines are likely lower than damages because of difficulties in detection, attribution, and enforcement, as discussed in Shavell (2007).

a poorly-targeted solution relative to directly subsidizing innovation or small firms. In another industry, reducing the number of firms might raise competitiveness concerns. In this case, even after the bond mandate, producers in Texas faced essentially perfect competition both within the state and from the world market. In summary, the results suggest that the judgment-proof problem had substantial welfare consequences, and that mitigating these problems through the bond requirement was very likely welfare-improving.

8 Conclusion

This paper focuses on a historical case study, but the results are relevant today. Between 2006 and 2013, U.S. oil and natural gas production increased by 65% and 40%, respectively. The boom has had economy-wide benefits. It also presents environmental challenges on a massive scale. The growth in production creates more opportunities for accidents, and the deployment of new chemicals and techniques creates novel risks. Whether or not new drilling continues at a similar pace, the huge number of recently-constructed wells will continue to operate for years.

At the same time, bond requirements in most jurisdictions remain very low. The minimum bond requirements for oil and gas production on federal lands have not been increased since 1960, even to adjust for inflation (Davis, 2015). Texas's bond requirements are some of the strictest among major oil- and gas-producing states.[41] This study supports arguments to increase bonds in other jurisdictions to at least the amounts required in Texas. While it is impossible to extrapolate beyond the observed levels, it seems likely that somewhat higher bond requirements would

[41] For a detailed state-by-state comparison of bonding requirements, see Dutzik et al. (2013).

yield further benefits given that Texas' requirements are still well below potential damages.

More broadly, the results suggest that bankruptcy should be taken seriously as a determinant of market structure in hazardous industries. The ability to avoid environmental costs through bankruptcy caused small, financially weak producers to invest less in environmental protection, and shifted production to those small firms. A surety bond requirement significantly reduced these distortions. Small firms produced less output with greater safety effort. Most of this output was re-allocated to large producers, but there was a decrease in the number of high-cost projects where social cost (including environmental cost) likely exceeded social benefit. Environmental outcomes improved sharply.

Within the energy sector, these results have implications for transportation of oil, natural gas, and gasoline and other refined products by pipeline, road, and rail.[42] Examples in other sectors include chemical manufacturing and transportation network companies. Further work in other settings will help to gauge the generality of these results, but this study supports concerns about the incentive effects of bankruptcy in dangerous industries. Continuing to evaluate and address this market failure will be an important component of efficient safety regulation in some of the world's most important industries.

[42] In 2013, an oil train explosion in Lac-Mégantic, Quebec killed 47. Damages were $200 million. The railroad declared bankruptcy and had only $25 million in liability insurance. Morris, Betsy. "Fiery Oil-Train Accidents Raise Railroad Insurance Worries." *Wall Street Journal*. Jan. 8, 2014.

Figure 1: The Judgment-Proof Problem With Heterogenous Firms

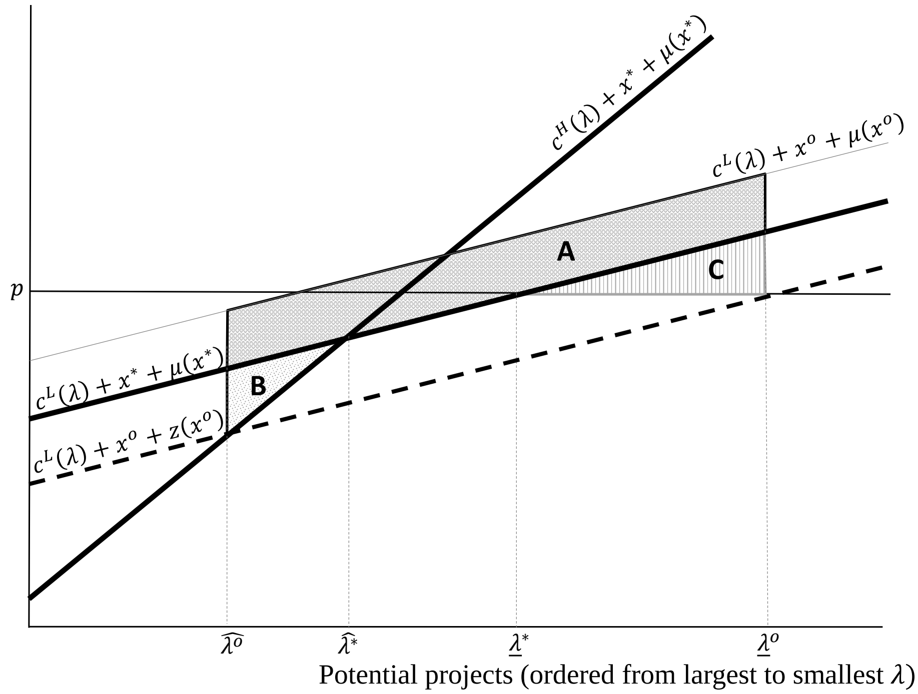


Figure 2: Environmental Incidents and Firm Size

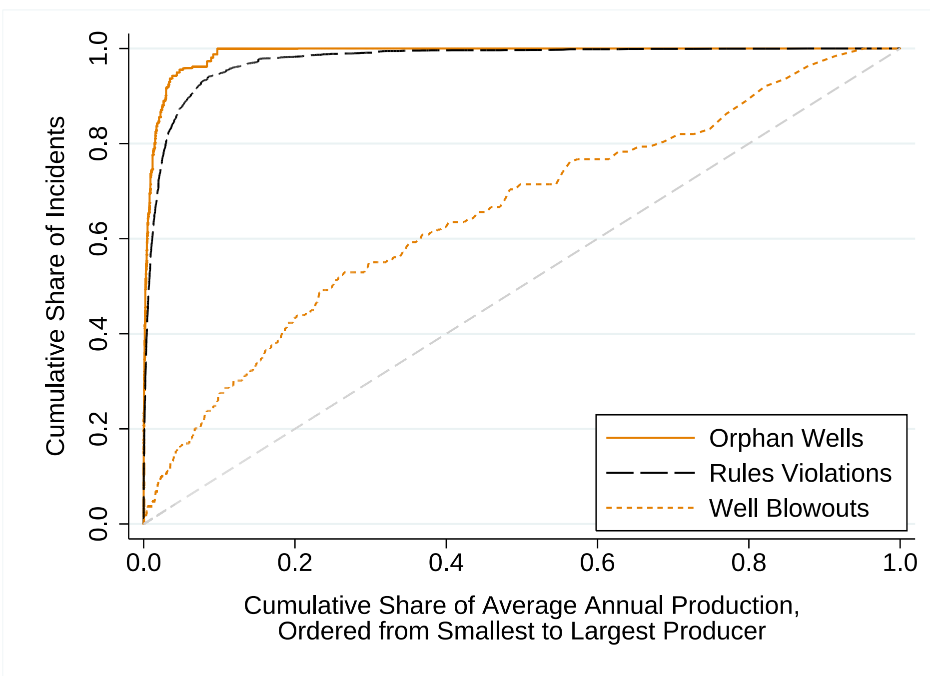


Figure 3: Number of Firms Exiting by Month

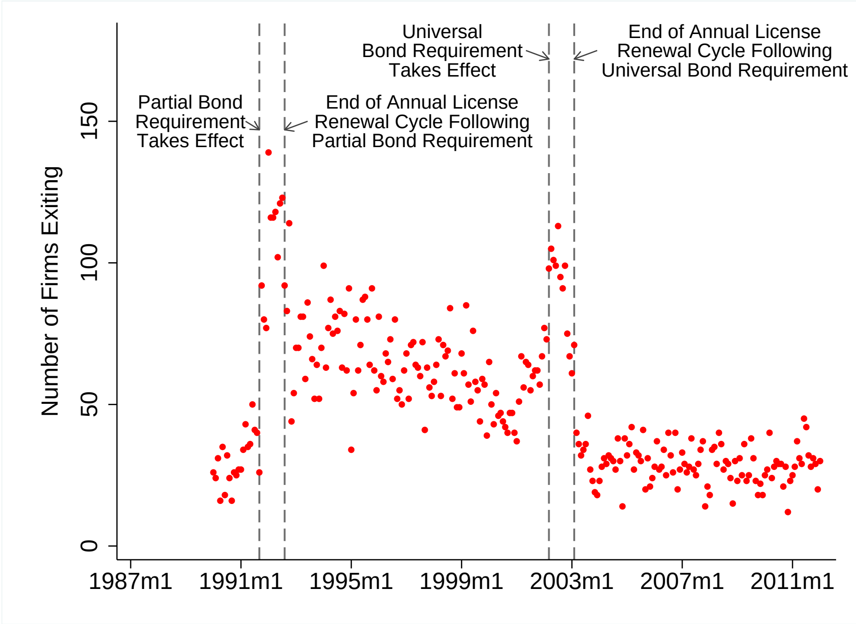


Figure 4: The Effect of the Bond Requirement on Exit

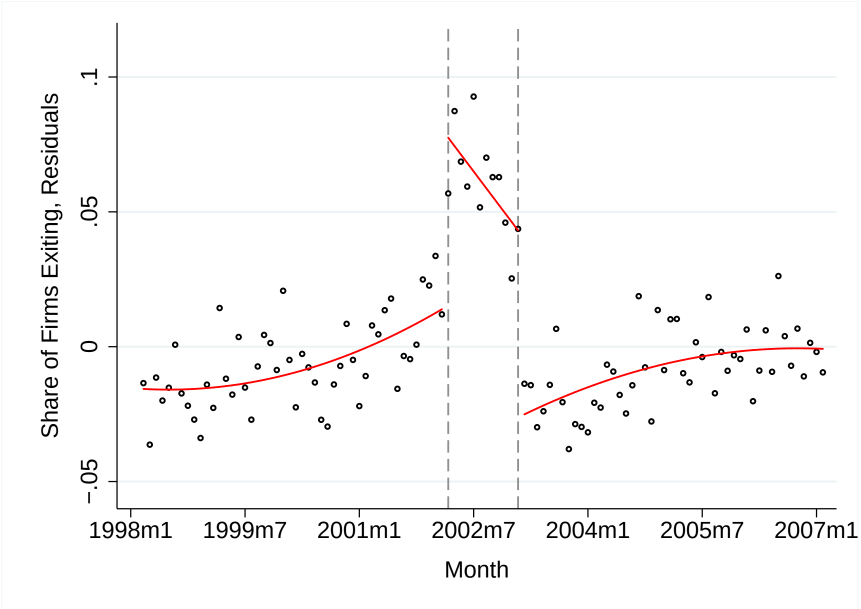
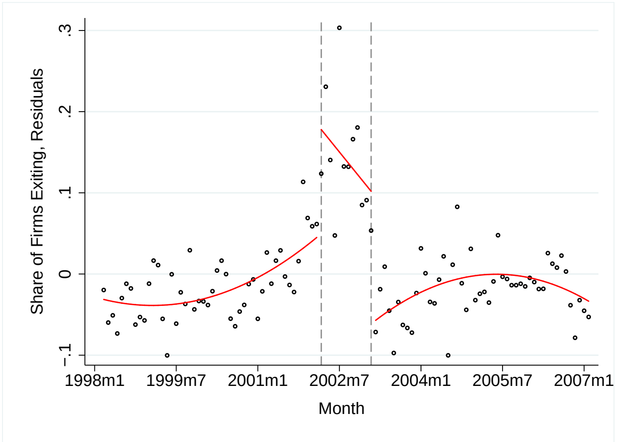


Figure 3 Notes: Exit date is 12 months after final annual license renewal. Vertical dashed lines show Sep. 1991–Aug. 1992 and Mar. 2002–Feb. 2003. Includes firms with production during 1990–2012; see Data Appendix for description of 1990–1992 production data.

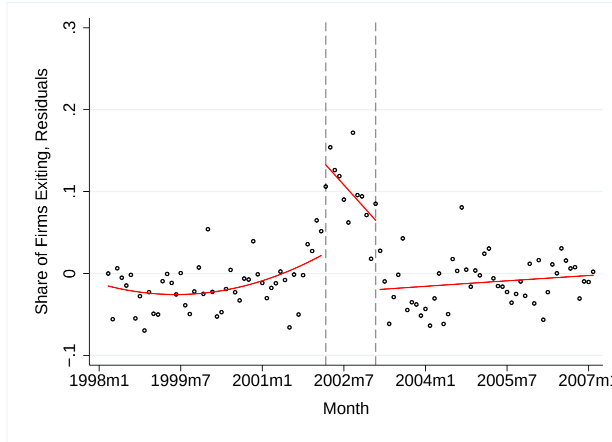
Figure 4 Notes: The sample includes Mar. 1998 to Feb. 2007. There is one observation per firm per year in the assigned license renewal month. Dots are monthly means of residuals from a regression of $1[Exit]$ on month-of-year fixed effects and monthly crude oil prices. The red curves show a quadratic polynomial for the pre-period, a separate linear polynomial for Mar. 2002–Feb. 2003, and a separate quadratic polynomial for the post-period.

Figure 5: The Effect of the Bond Requirement on Exit, by Firm Size

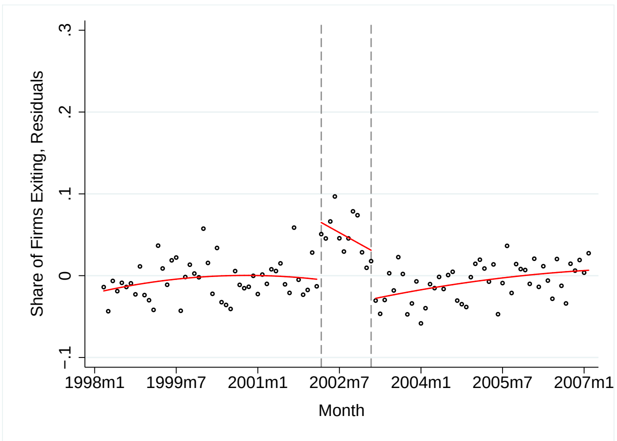
(a) 1st Quintile



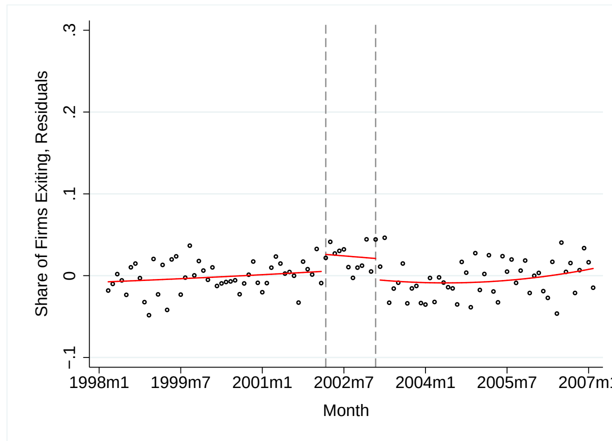
(b) 2nd Quintile



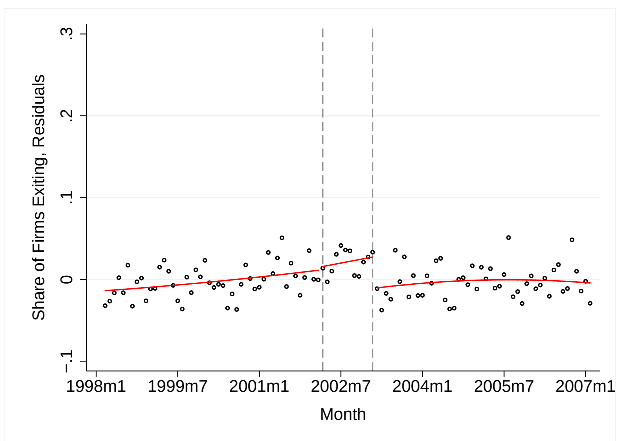
(c) 3rd Quintile



(d) 4th Quintile



(e) 5th Quintile



Notes: Each panel reproduces Figure 4 for a single quintile of the output distribution. Output is calculated as average annual production during 1997–2008 in barrel-of-oil equivalents (BOE). Average annual production is 12 times the average monthly production across all non-zero months. The quintile cutoffs are listed in Appendix Table 1.

Figure 6: Number of Very Low-Producing Leases

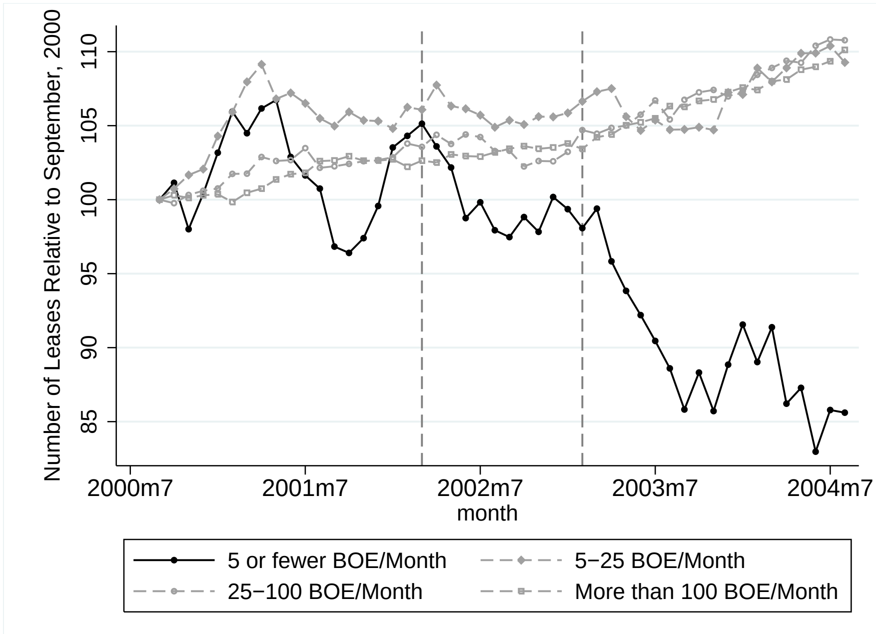


Figure 7: Average Rate of Well Orphaning By Month

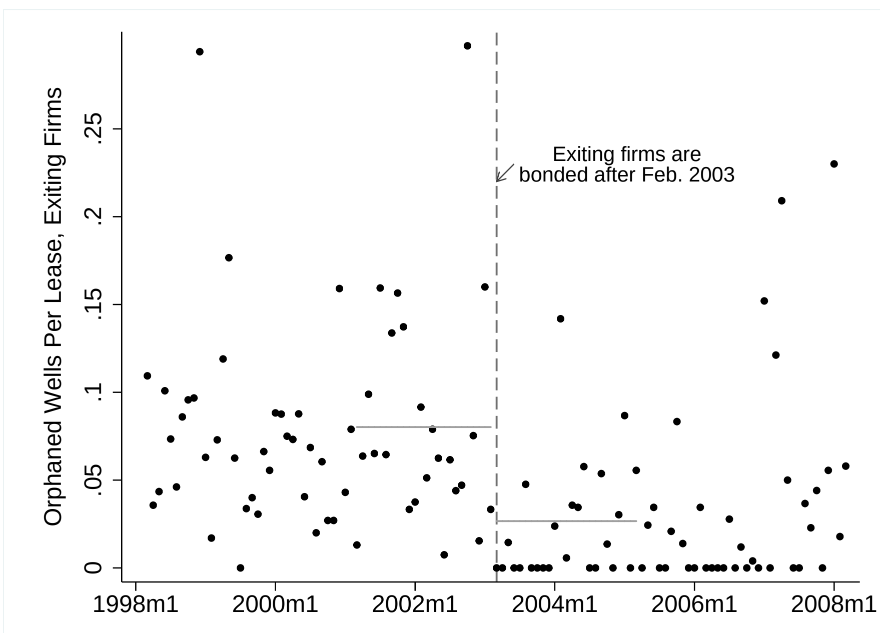


Figure 6 Notes: Monthly production at the lease level is calculated as the 6-month running average of oil and natural gas production in barrel-of-oil equivalents. Counts are normalized relative to September, 2000.

Figure 7 Notes: This figure shows the average rate of well orphaning (wells per lease) among firms exiting each month. The gray horizontal bars show means for two years before and two years after February, 2003.

Figure 8: Water Protection Rules Violations by Month

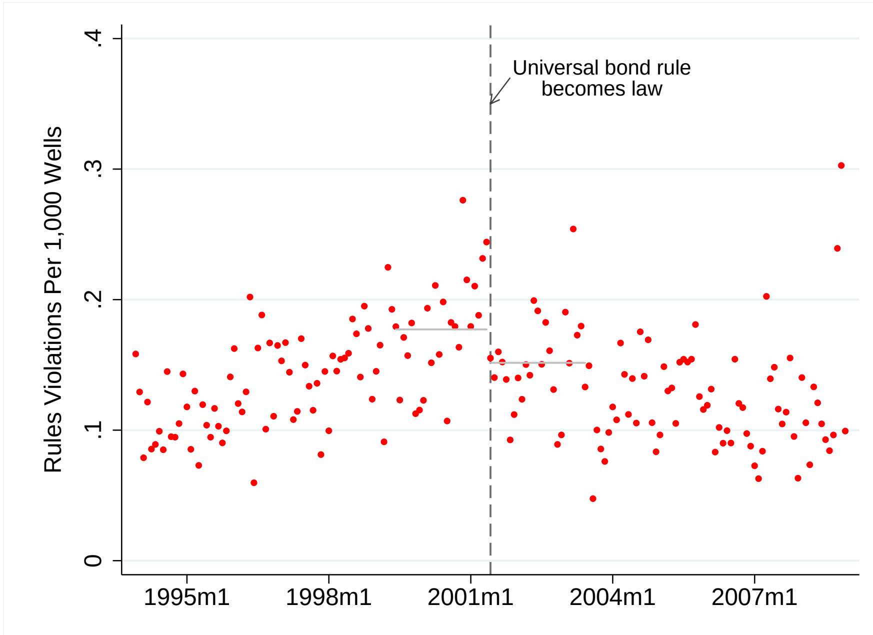


Figure 9: Well Blowouts by Quarter

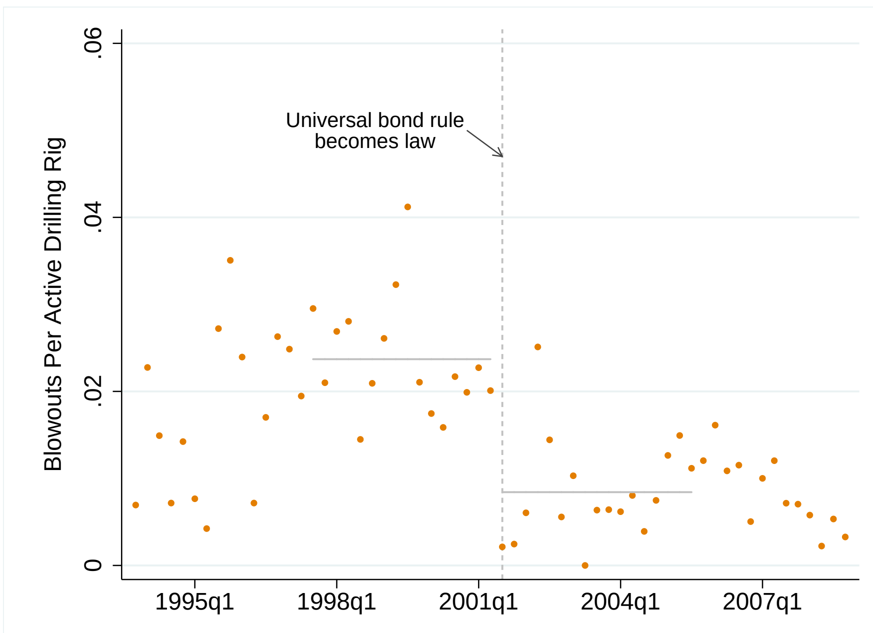


Figure 8 Notes: This figure shows the number of violations of Statewide Rules 8 and 14 per 1,000 wells, by month. The gray horizontal bars show means for two years before and after June, 2001.

Figure 9 Notes: This figure shows the number of blowouts per active drilling rig, by quarter. Rig data come from the Baker Hughes Historical Rig Count dataset. The gray horizontal bars show means for four years before and after June, 2001.

Table 1: Effect of the Bond Requirement on Exit

	(1)	(2)	(3)
Begin Rollout	0.060***	0.062***	0.061***
	(0.011)	(0.010)	(0.008)
Oil Price		-0.050	-0.074^{**}
($100/bbl)		(0.032)	(0.031)
Constant	0.101***	0.100***	0.100***
	(0.006)	(0.005)	(0.007)
Month-of-year FE	No	No	Yes
Local Time Polynomial	Yes	Yes	Yes
N	53,383	53,383	53,383
Firms	9,095	9,095	9,095

Notes: This table reports the results of 3 separate OLS regressions. The sample includes March, 1998 to February, 2007. The data are a monthly panel with one observation per firm per year, in the firm's assigned license renewal month. The dependent variable is an indicator variable equal to one in the month of exit. Begin Rollout is an indicator variable equal to one starting in March, 2002. All specifications include a quadratic polynomial in time for the pre-period; a separate linear polynomial for the implementation year; a separate quadratic polynomial for the post-period, and an indicator variable equal to one starting in March, 2003 ("End Rollout"). Oil prices are monthly average Texas first purchase prices in the month of license renewal, in hundreds of 2010 dollars. Standard errors are clustered by quarter. *** indicates statistical significance at the 1% level; ** at the 5% level; * at the 10% level.

Table 2: Effect of the Bond Requirement on Exit by Output Quintile

	(1) Quintile 1	(2) Quintile 2	(3) Quintile 3	(4) Quintile 4	(5) Quintile 5
Begin Rollout	0.127***	0.110***	0.069***	0.019**	0.001
	(0.017)	(0.019)	(0.013)	(0.008)	(0.013)
Oil Price	−0.265***	−0.007	−0.137**	0.028	−0.039
($100/bbl)	(0.061)	(0.061)	(0.051)	(0.032)	(0.055)
Constant	0.174***	0.134***	0.071***	0.067***	0.067***
	(0.016)	(0.018)	(0.010)	(0.008)	(0.010)
N	8,754	9,794	10,930	12,069	11,836
Firms	1,739	1,791	1,817	1,868	1,880

Notes: This table reports estimates separately by output quintile for the regression specification shown in Column 3 of Table 1. All regressions include month-of-year fixed effects, the same local polynomial in time as in Table 1, and an indicator variable equal to one starting in March, 2003 ("End Rollout"). The output quintile cutoffs are listed in Appendix Table 1. Output is calculated as average annual production during 1997–2008 in barrels of oil equivalent (BOE). Average annual production is 12 times the average monthly production across all non-zero months. Standard errors are clustered by quarter. *** indicates statistical significance at the 1% level; ** at the 5% level; * at the 10% level.

Table 3: Lease Transfers During the Implementation Year

	(1) Implementation Year	(2) Adjacent Years	(3) Difference: (1) - (2)
Panel A. Transfers from All Firms			
Overall Transfer Probability	3.61%	2.75%	0.86%***
Transfer to Larger Firm	2.05%	1.40%	0.66%***
Transfer to Smaller Firm	1.37%	1.19%	0.18%***
Lease-Year Observations	118,612	724,524	
Panel B. Transfers from the Smallest 80% of firms			
Overall Transfer Probability	13.66%	10.53%	3.13%***
Transfer to Larger Firm	9.40%	6.36%	3.04%***
Transfer to Smaller Firm	3.47%	3.43%	0.04%
Lease-Year Observations	24,807	150,202	

Notes: This table reports annual transfer probabilities for oil and gas leases during March 2002–February 2003 and six adjacent twelve-month periods (three before and three after). "Transfer to Larger Firm" includes transfers where the receiving firm had more leases than the selling firm (at the start of the year). "Transfer to Smaller Firm" is the opposite. Transfers are identified as changes in the responsible operator. To focus on movements that were plausibly related to the bond requirement, I ignore transfers where both the buyer and seller are in the top 10% of annual production. This removes the influence of a handful of mergers involving hundreds or thousands of leases (for example, the Chevron–Texaco merger). *** indicates differences that are statistically significant differences at the 1% level; ** at the 5% level; * at the 1% level.

Table 4: Effect of Bonding on Oil and Gas Production for Bonded Firms

	(1)	(2)	(3)	(4)
1[Bonded]	-0.067^{***}	-0.035^{***}		
	(0.010)	(0.011)		
1[Bonded]*Quintiles 1 – 4			-0.047^{***}	
			(0.013)	
1[Bonded]*Quintile 1				-0.095^{*}
				(0.051)
1[Bonded]*Quintile 2				-0.063^{**}
				(0.028)
1[Bonded]*Quintile 3				-0.053^{**}
				(0.024)
1[Bonded]*Quintile 4				-0.007
				(0.015)
1[Bonded]*Quintile 5			0.002	0.002
			(0.014)	(0.014)
Constant	6.722^{***}	6.638^{***}	6.637^{***}	6.632^{***}
	(0.004)	(0.013)	(0.012)	(0.012)
Firm Fixed Effects	Yes	Yes	Yes	Yes
Month-by-Quintile FE	No	Yes	Yes	Yes
N	52,297	52,297	52,297	52,297
Firms	4,648	4,648	4,648	4,648

Notes: This table reports the results of 4 separate regressions. The dependent variable is the log of monthly oil and gas production in barrel-of-oil equivalents. The sample is limited to March 2002 – February 2003, and to firms that renewed their annual operating license during that period. $1[Bonded]$ is an indicator variable equaling one in all months after a firm's license renewal month. The output quintile cutoffs are listed in Appendix Table 1, and are based on average annual production during the three years before the bond requirement. Standard errors are clustered at the operator level. *** indicates statistical significance at the 1% level; ** at the 5% level; * at the 1% level.

Table 5: Effect of the Bond Requirement on Orphan Wells

		Firm Size Quintile				
	All Firms	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
1[Bonded]	-0.068^{***}	-0.125^{*}	-0.067^{**}	-0.055^{**}	-0.007	-0.002
	(0.019)	(0.071)	(0.026)	(0.023)	(0.028)	(0.012)
Constant	0.081^{***}	0.146^{***}	0.087^{***}	0.058^{***}	0.030^{***}	0.010
	(0.014)	(0.050)	(0.020)	(0.019)	(0.010)	(0.008)
Time Trend	Yes	Yes	Yes	Yes	Yes	Yes
Firms	4,394	1,133	989	829	751	692

Notes: This table reports six separate regressions. The sample includes firms that exited between March, 1998 and March, 2008. The dependent variable is the number of orphan wells left by the firm, divided by the number of leases operated. There is one observation per firm, in its month of exit. All regressions include a quadratic polynomial in month of exit. The output quintile cutoffs are listed in Appendix Table 1. Standard errors are clustered by quarter. *** indicates statistical significance at the 1% level; ** at the 5% level; * at the 10% level.

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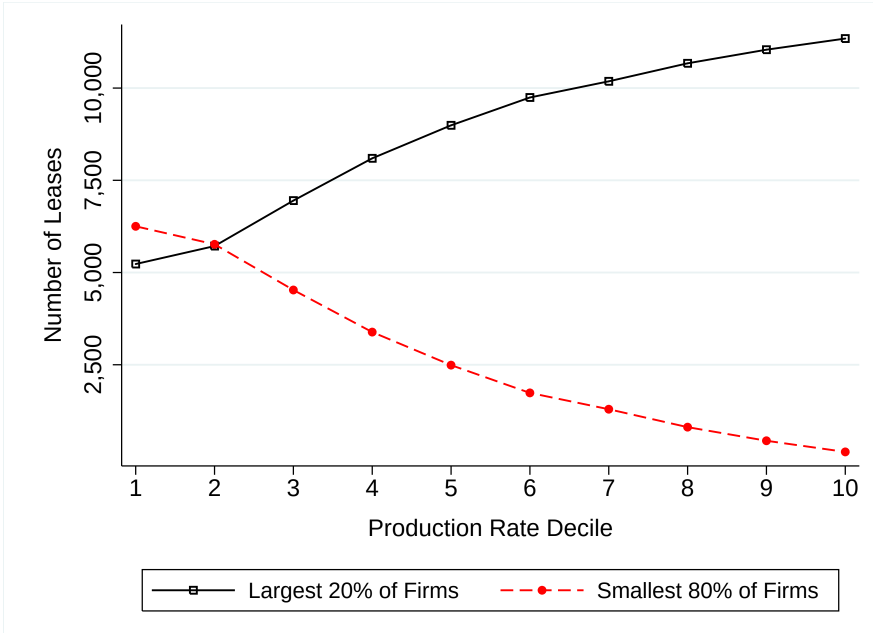
APPENDIX 1 – ADDITIONAL RESULTS – FOR ONLINE PUBLICATION

Appendix Figure 1: Lease-level Production Rates, By Firm Size



Appendix Figure 2: Trend in Exit During Implementation, Dropping Last 3 Months

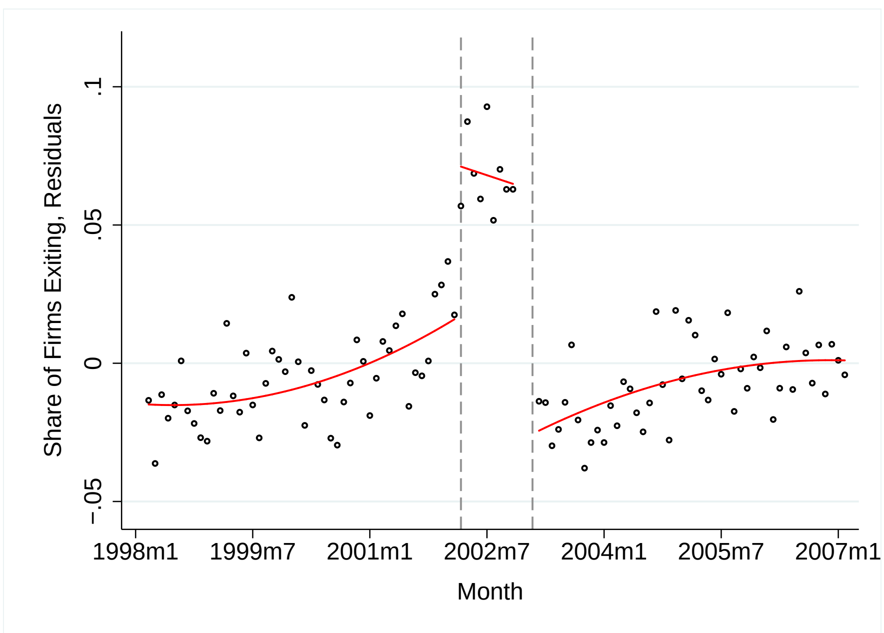
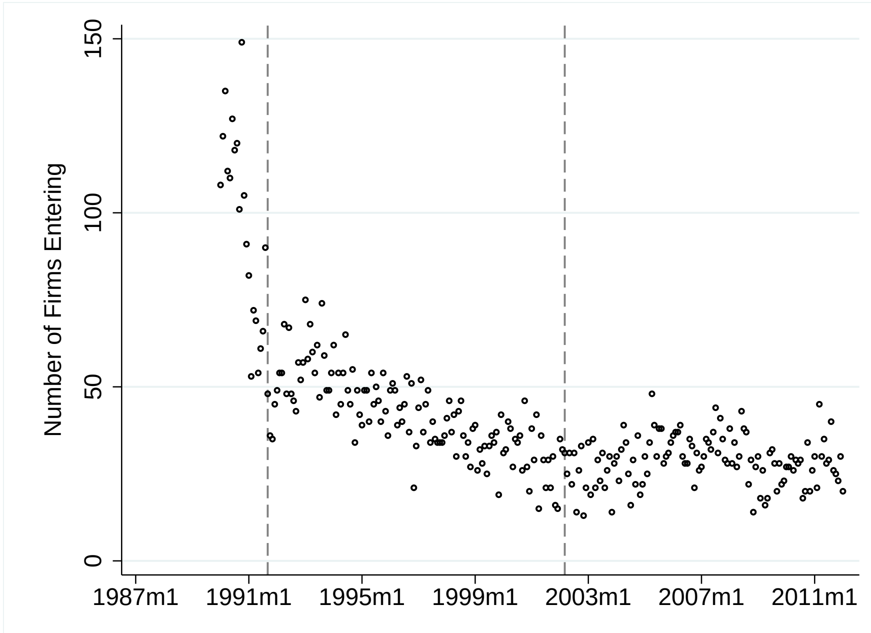


Figure 1 Notes: The horizontal axis shows deciles of production rate for all oil and gas leases in 2000. Dots show the total number of leases operated by small and large firms.

Figure 2 Notes: This figure is constructed identically to Figure 4 but excludes Dec. 2002–Feb. 2003, when a court ruling temporarily limited full enforcement of the bond requirement.

Appendix Figure 3: Entry by Month



Appendix Figure 4: Net Entry (Entry - Exit) by Month

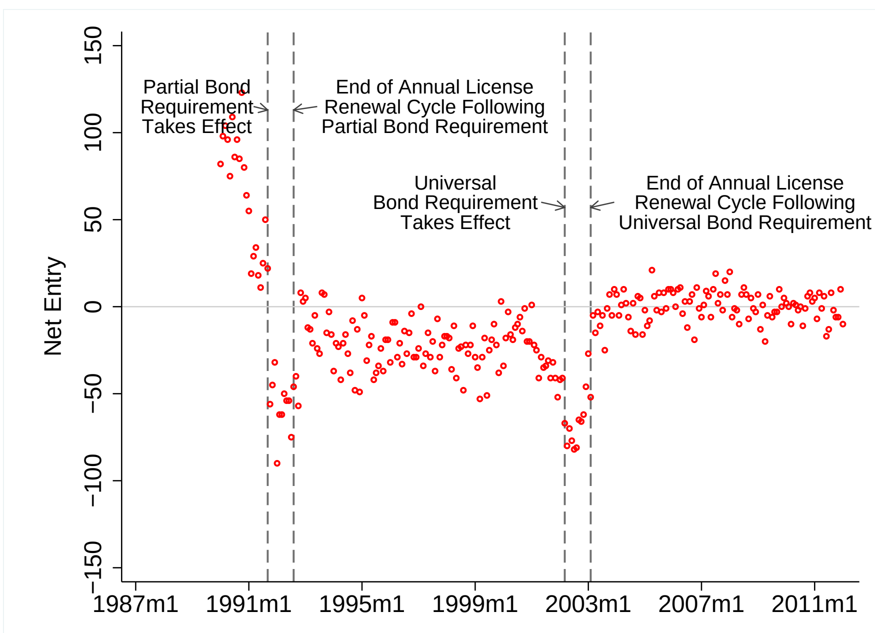
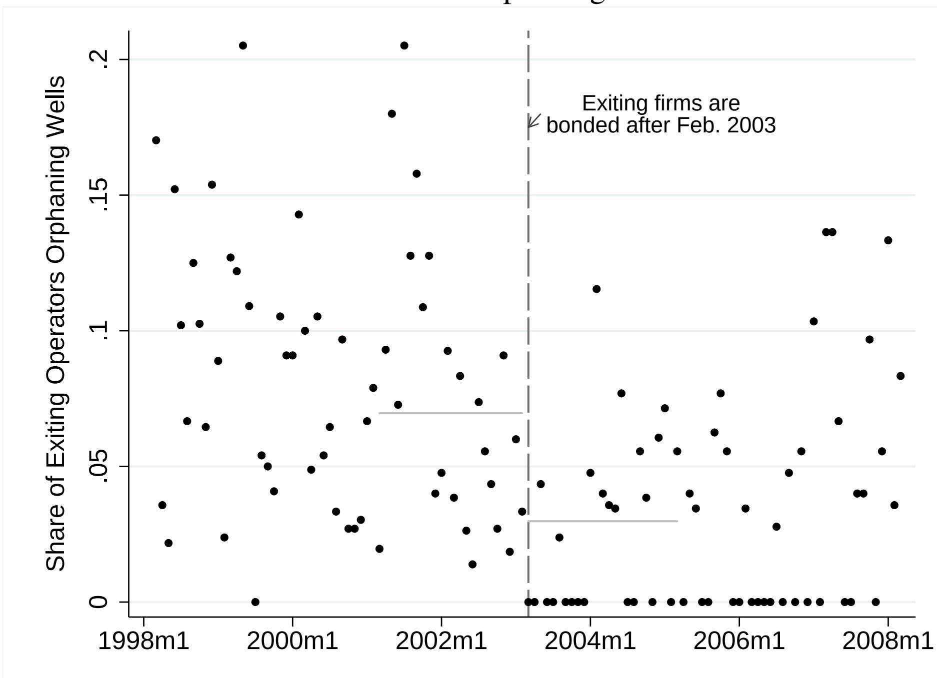


Figure 3 Notes: This figure shows the number of firms entering the industry each month. Entry date is defined as the date of the firm's first annual operating license filing. The vertical dashed lines show September, 1991 and March, 2002. The sample includes all firms with oil or gas production from 1990 to 2010.

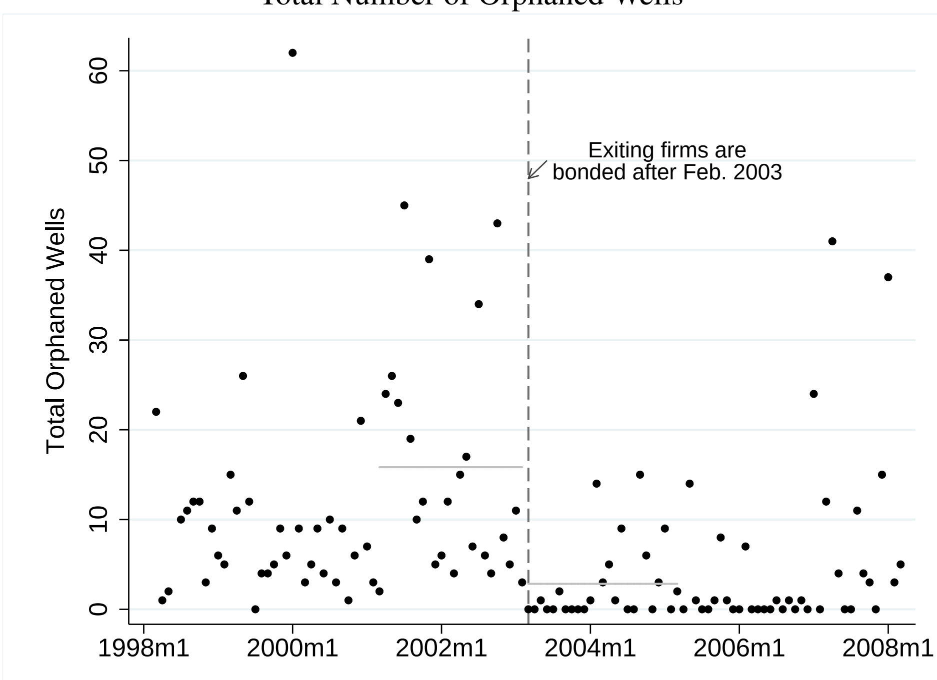
Figure 4 Notes: This figure shows the net change in the number of firms in the industry each month. Vertical dashed lines show Sep. 1991–Aug. 1992 and Mar. 2002–Feb. 2003.

Appendix Figure 5: Alternative Measures of Well Orphaning

Share of Exiters Orphaning Wells



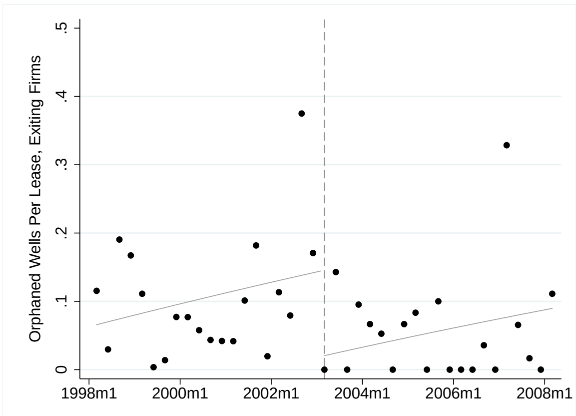
Total Number of Orphaned Wells



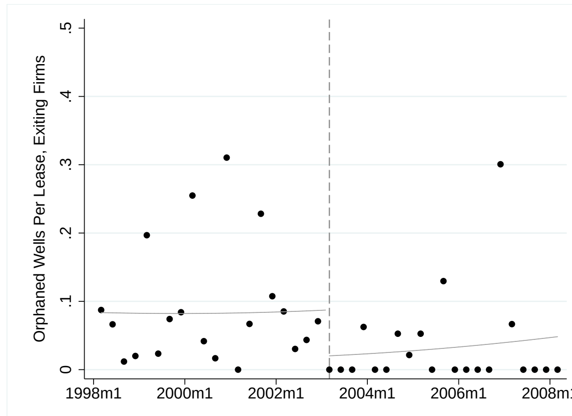
Notes: The top panel shows the the share of exiting firms each month that left behind any orphan wells. The bottom panel shows the total number of wells orphaned each month. In the bottom panel, one pre-period outlier month with 110 orphan wells (June, 1998) is not shown.

Appendix Figure 6: Effect of the Bond Requirement on Orphan Wells, by Firm Size

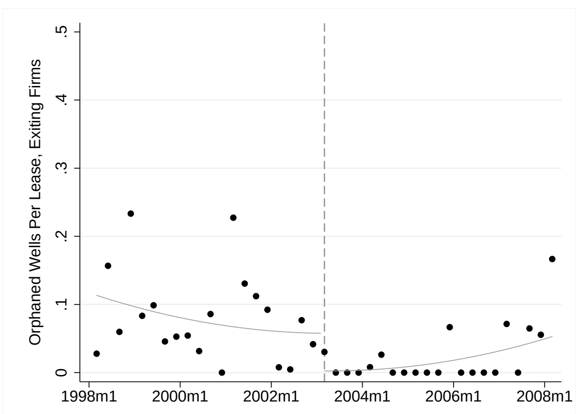
(a) 1st Quintile



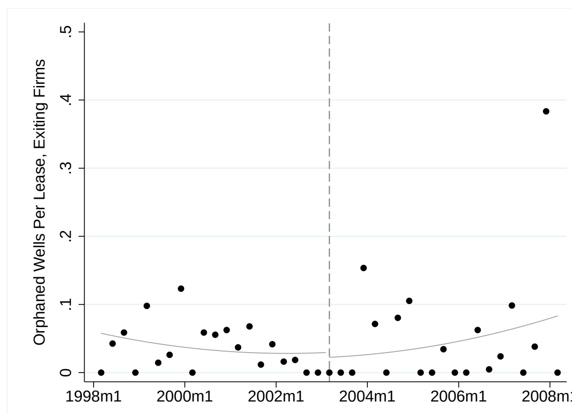
(b) 2nd Quintile



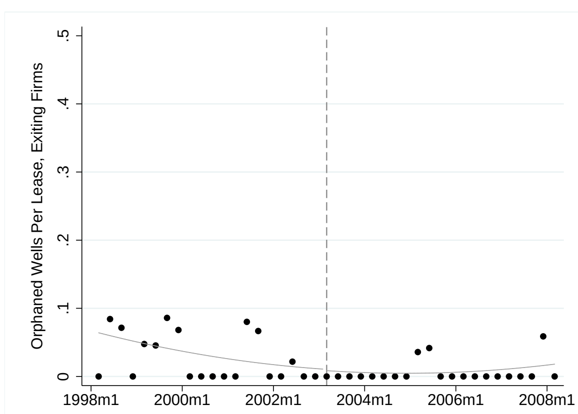
(c) 3rd Quintile



(d) 4th Quintile

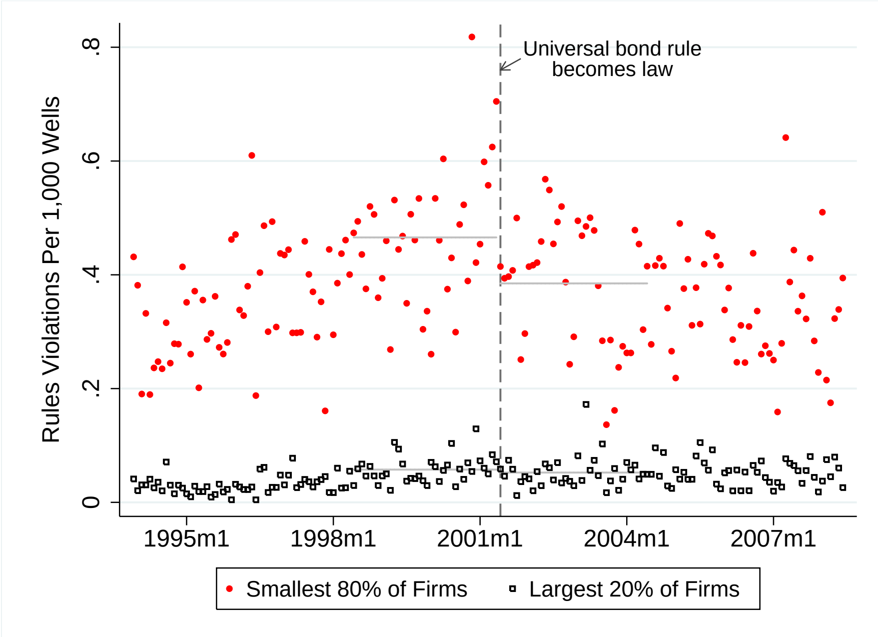


(e) 5th Quintile



Notes: Each panel shows the rate of well orphaning (orphan wells per lease) by month within a single size quintile. The gray lines show a quadratic polynomial in time. The output quintile cutoffs are listed in Table 1.

Appendix Figure 7: Water Protection Rules Violations by Month and Firm Size



Appendix Figure 8: Well Blowouts in Louisiana by Quarter

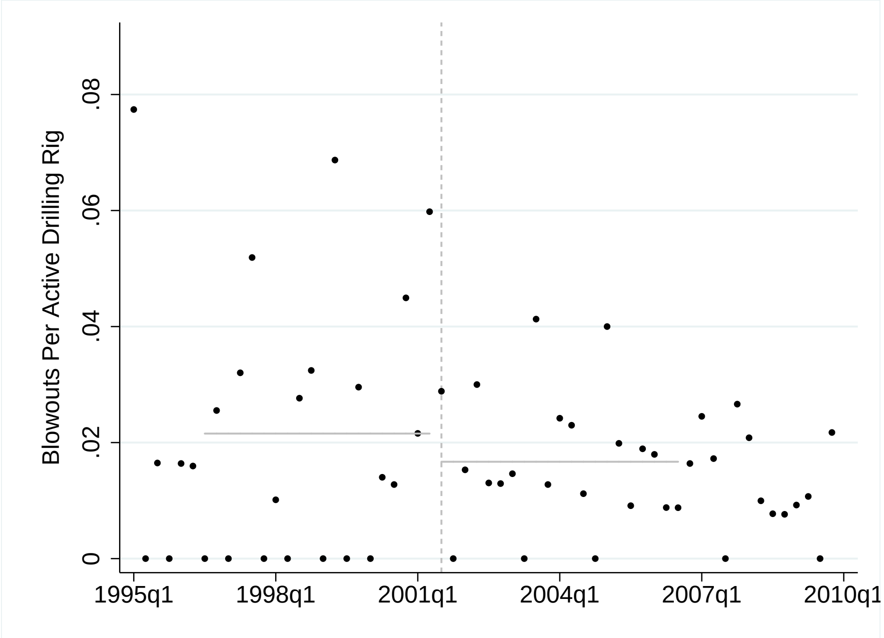
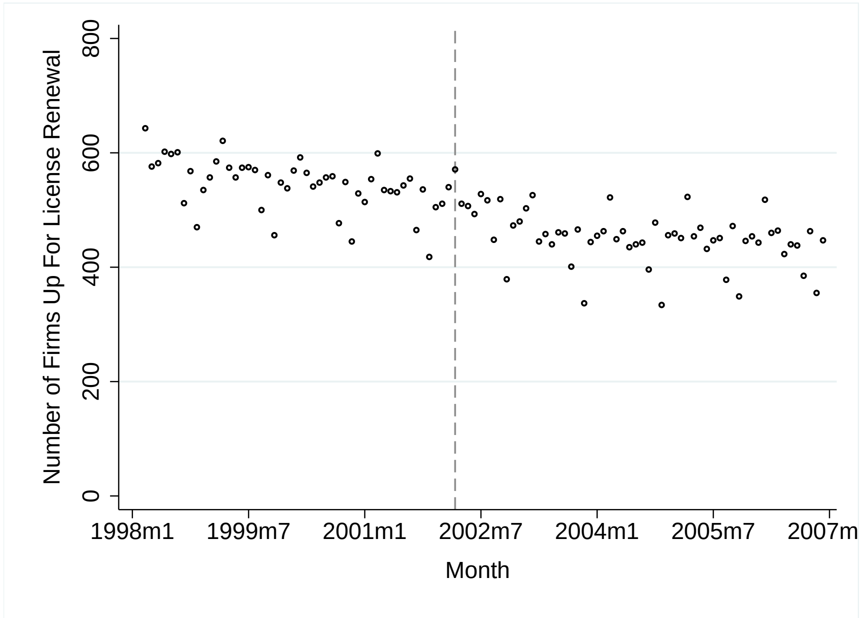


Figure 7 Notes: This figure reproduces Figure 8, showing the smallest 80% and largest 20% of firms separately.

Figure 8 Notes: This figure shows the rate of onshore well blowouts in Louisiana. The fitted lines represent the mean rate of blowouts during the six years before and six years after June 2001.

Appendix Figure 9: Number of Firms Up For License Renewal Each Month



Appendix Figure 10: Low-Producing Leases vs. Output Price

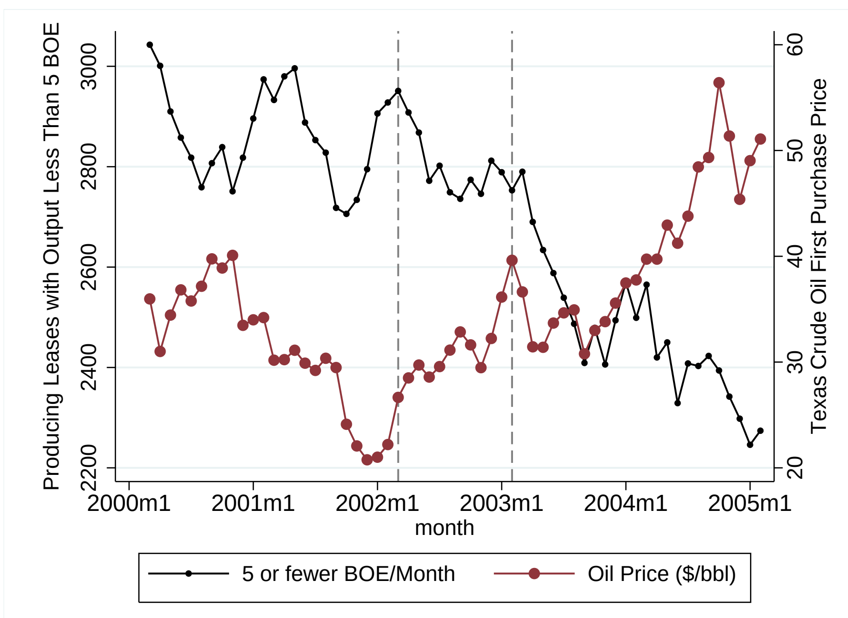


Figure 9: This figure shows the number of operators assigned to renew their annual license each month. The dashed line is March, 2002.

Figure 10: Output is a six-month running average. Oil and natural gas prices moved very similarly during this period. I show oil prices because 68% of low-producing leases are classified as oil leases.

Appendix Table 1: Percentiles of Annual Production and Revenue

Percentile	Production (BOE)	Revenue (Dollars)
Max	85,666,656	3,228,537,088
80	47,548	1,561,564
60	10,576	343,567
40	3,510	110,314
20	1,104	33,052

Notes: This table lists quintile cutoffs for output and revenue for the 10,489 operators in the sample. Annual production and revenue are calculated for each firm as twelve times the average value in all non-zero months between March 1997 and February 2008. One barrel-of-oil equivalent is one barrel of oil or six thousand cubic feet of natural gas. Revenues are calculated using EIA Texas first purchase prices for oil and EIA Texas wellhead prices for natural gas. Dollar amounts are in 2010 dollars.

Appendix Table 2: Environmental Compliance History of Exiting Firms

	All Firms	Firms With 10 or Fewer Leases	Firms With 3 or Fewer Leases
Panel A. Negative Binomial			
1[Exit]	0.30 (0.11)***	0.33 (0.14)**	0.20 (0.24)
Constant	-3.35 (0.05)***	-3.12 (0.07)***	-3.02 (0.12)***
% Difference	**35%**	**39%**	**22%**
Panel B. OLS			
1[Exit]	0.014 (0.007)**	0.017 (0.009)*	0.013 (0.015)
Constant	0.039 (0.002)***	0.045 (0.004)***	0.049 (0.007)***
% Difference	**37%**	**37%**	**28%**
Observations	5,690	3,177	1,563

Notes: This table reports the results of six separate regressions. In each case, the sample includes all firms in the market in March 2002 that had at least 12 months of production history during the previous 10 years. The dependent variable is the count of violations of Statewide Rule 8 and Statewide Rule 14 during the 10-year period ending in March 2002, normalized by the number of leases operated. For the negative binomial regressions the log of the number of leases is included as an independent variable with coefficient constrained to one. For the OLS regressions, the dependent variable is divided by the number of leases. $1[Exit]$ is an indicator variable equal to one for firms that exited during March, 2002 – February, 2003. For OLS, the percentage change in expected count is the regression coefficient (ϕ) divided by the sample mean prior to the policy change. For negative binomial, the percentage change in expected count is $e^{\phi} - 1$. Standard errors are bootstrapped with 500 repetitions. *** indicates statistical significance at the 1% level; ** at the 5% level; and * at the 10% level.

Appendix Table 3: Changes in Rules Violations and Well Blowouts

	Water Protection Rules Violations		Well Blowouts	
	(1)	(2)	(3)	(4)
$1[After]$	-0.139^{**} (0.070)	-0.275^{*} (0.146)	-0.509^{***} (0.160)	-1.272^{***} (0.288)
% Change in Expected Count	−13%	−24%	−40%	−72%
Constant	-7.936^{***} (0.045)	-7.908^{***} (0.109)	-9.435^{***} (0.076)	-8.955^{***} (0.232)
Time Trend	None	Exponential	None	Exponential
Month-of-Year FE	No	Yes	No	Yes
Normalization	Wells Operated	Wells Operated	Drilling Permits	Drilling Permits
N	695,575	695,575	228,437	228,437
Firms	9,814	9,814	5,267	5,267

Notes: This table reports the results of four separate negative binomial regressions. The sample period covers June 1996 to June 2006. $1[After]$ is an indicator variable equal to one after June, 2001. In Columns (1) and (2) the dependent variable is the monthly count of violations of Statewide Rules 8 or 14, normalized by the number of wells operated. The sample includes all firm-months with positive oil or gas production. In Columns (3) and (4) the dependent variable is the monthly count of well blowouts, normalized by the number of active drilling permits held by the operator. The sample includes all firm-months with drilling activity. In all cases, the normalization is implemented by including the log of the normalizing quantity as a regressor with coefficient constrained to one. The percentage change in expected count is $e^{\phi} - 1$, where ϕ is the regression coefficient. Standard errors are clustered by quarter. *** indicates statistical significance at the 1% level; ** at the 5% level; and * at the 10% level.

Appendix Table 4: Effect on Exit, Alternative Bandwidths

	RD Bandwidth in Months			
	48	**60**	**36**	**24**
Begin Rollout	0.061***	0.074***	0.048***	0.046***
	(0.008)	(0.009)	(0.011)	(0.009)
Oil Price	−0.074**	−0.093***	−0.026	−0.083
($100/bbl)	(0.031)	(0.024)	(0.051)	(0.051)
Constant	0.100***	0.088***	0.111***	0.115***
	(0.007)	(0.008)	(0.009)	(0.007)
Month-of-year FE	Yes	Yes	Yes	Yes
Local Time Polynomial	Yes	Yes	Yes	Yes
N	53,383	65,362	41,272	29,311
Firms	9,095	9,589	8,324	7,467

Notes: This table reproduces Column (3) of Table 1 using different RD bandwidths. The bandwidth listed at the top of each column is the number of months before and after the implementation year that are included in the regression. The first column is the same specification as Table1.

Appendix Table 5: Comparing Firms by License Renewal Month

Month	(1) Number of Firms	(2) Annual Production ($1,000)	(3) Number of Leases
January	719	1,687 (6,165)	14 (33)
February	761	1,922 (6,743)	15 (36)
March	818	1,787 (6,635)	14 (32)
April	728	1,162 (4,744)	11 (21)
May	732	1,667 (6,480)	12 (26)
June	759	1,842 (7,169)	15 (37)
July	730	1,516 (6,250)	13 (30)
August	751	1,376 (5,062)	13 (38)
September	655	1,657 (6,086)	13 (23)
October	727	1,161 (4,251)	12 (23)
November	593	1,541 (5,801)	13 (31)
December	673	1,811 (6,141)	16 (36)
F statistic		1.29	1.26
p-value		0.22	0.24

Notes: This table reports mean revenue and number of leases for firms according to their assigned license renewal month. Standard deviations are in parentheses. This table covers firms from their 1996 to 2001 license renewals. Annual revenue is twelve times the average value of monthly oil and natural gas production, calculated using oil and gas prices in each month. To reduce the influence of a few very large firms, I drop firms larger than the 99th percentile of annual average production value (for this table only). The F statistic and p-value are for a test of the null hypothesis that the mean of average annual production is the same in every group.

Appendix Table 6: Effect of License Renewal on Production in Other Years

	(I) Implementation Year	(II) Earlier Years	(III) Later Years
1[Bonded]*Quintiles 1 – 4	-0.047^{***}	-0.005	-0.009
	(0.013)	(0.007)	(0.007)
N	52,297	183,403	137,207
Firms	4,648	6,552	5,569

Notes: This table reports estimates from 3 separate regressions showing the impact of renewing the annual operating license on firm-level oil and gas production in various years. Using the approach described for Table 4, similar samples are constructed for the three years before and the three years after the implementation of the bond requirement. Column (I) of this table is identical to Column (3) of Table 4. Column (II) of this table pools the three years prior to the implementation year; and Column (III) pools the three years after the implementation year. Standard errors are clustered at the operator level. *** indicates statistical significance at the 1% level; ** at the 5% level; * at the 1% level.

Appendix Table 7: Texas Regulations Implemented in 2001 and 2002

Action	Proposed	Implemented
Allows electronic filing of drilling permits	March 2001 (TXR 26 2257)	June 2001 (TXR 26 4088)
Clarifies wording of hazardous waste rules[1]	May 2001 (TXR 26 3431)	September 2001 (TXR 26 6870)
Extends existing tax credit for high-cost gas	June 2001 (TXR 26 4015)	August 2001 (TXR 26 6009)
Extends existing tax credit for marginal wells	July 2001 (TXR 26 3431)	September 2001 (TXR 26 6869)
Implements Senate Bill 310 (bonding)[2]	**August 2001** (TXR 26 5919)	**March 2002** (TXR 27 139)
Clarifies rules for assigning acreage to pooled units	October 2001 (TXR 26 7721)	January 2002 (TXR 27 150)
Clarifies rules for requesting end to unitization	November 2001 (TXR 26 9480)	February 2002 (TXR 27 906)
Clarifies rules for transporting oil and gas	January 2002 (TXR 27 547)	May 2002 (TXR 27 3756)
Clarifies rules for "swabbing" existing wells[3]	April 2002 (TXR 27 2666)	September 2002 (TXR 27 9149)

Notes: This table lists all rules changes for oil and gas producers implemented by the Texas Railroad Commission during 2001 and 2002. It is based on all rule introductions or amendments listed in the RRC Oil and Gas Division rules (Texas Administrative Code, Title 16, Part 1, Chapter 3). "TXR" refers to volume and page number in the Texas Register. The date proposed is the date that the rule was published as a "Proposed Rule" to allow for public comment. The date implemented is the date that the regulation was published as an "Adopted Rule".

[1]This was a technical change in wording to match federal law, changing the word "facility" to "site." The proposed rule states, "The language change is consistent with the way the commission has applied the rule in that the commission's intent and policy, since the initial adoption of §3.98 in 1996, has been to apply the provisions of subsection (e) to oil and gas waste generators. Therefore, no one will be affected that was not affected under the previous rule."

[2]SB 310 passed the Texas legislature in June 2001; the RRC rule implementing SB 310 was first published as a proposed rule in August, 2001. This version was withdrawn and a second proposed rule was published in November, 2001 (TXR 26 8937).

[3] Swabbing is a technique that involves pulling fluid through the well bore using a wire and cup assembly. This rule clarifies that swabbing is prohibited as an ongoing production method to extend the life of very old wells.

1.1 Accounting for Related Operators

The Organization Report data identifies some sets of operators as having related ownership (e.g. name changes). Of the 10,489 total operators, 1,175 are identified as being related to at least one other operator. Collapsing related operators into single groups leaves 9,888 firm groups. This section reproduces key tables from the analysis using the collapsed data. In each case, the results are very similar to those in the main text. I choose not to collapse related operators in the main results because it is not clear how to treat some operator-specific fields when collapsing. For example, if related operators have different assigned license renewal months, the analysis in Table 4 would require me to choose which renewal month to use for the collapsed firm group.

In all of the tables in this section, the size quintile cutoffs are the same as those used in the main analysis.

Appendix Table 8: Reproducing Table 2, Collapsing Related Operators

	(1) **Quintile 1**	(2) **Quintile 2**	(3) **Quintile 3**	(4) **Quintile 4**	(5) **Quintile 5**
Begin Rollout	0.134^{***}	0.097^{***}	0.070^{***}	0.025^{***}	0.009
	(0.017)	(0.021)	(0.019)	(0.009)	(0.013)
Oil Price	-0.253^{***}	−0.029	-0.111^{*}	0.015	−0.049
($100/bbl)	(0.061)	(0.062)	(0.056)	(0.034)	(0.050)
Constant	0.164^{***}	0.131^{***}	0.068^{***}	0.055^{***}	0.049^{***}
	(0.015)	(0.019)	(0.011)	(0.008)	(0.009)
N	8,510	9,741	10,696	11,701	11,567
Firm Groups	1,661	1,736	1,732	1,742	1,702

APPENDIX 1 – ADDITIONAL RESULTS – FOR ONLINE PUBLICATION

Appendix Table 9: Reproducing Table 5, Collapsing Related Operators

		Firm Size Quintile				
	All Firms	(1)	(2)	(3)	(4)	(5)
1[Bonded]	-0.074^{***}	-0.130^{*}	-0.064^{**}	-0.067^{**}	-0.008	-0.007
	(0.022)	(0.077)	(0.027)	(0.025)	(0.031)	(0.014)
Constant	0.088^{***}	0.152^{***}	0.089^{***}	0.065^{***}	0.032^{***}	0.013
	(0.016)	(0.053)	(0.021)	(0.021)	(0.010)	(0.011)
Time Trend	Yes	Yes	Yes	Yes	Yes	Yes
Firm Groups	3,906	1,072	929	750	644	511

Appendix Table 10: Reproducing Appendix Table 3, Collapsing Related Firms

	(1) Implementation Year	(2) Adjacent Years	(3) Difference: (1) - (2)
Panel A. Transfers from All Firms			
Overall Transfer Probability	3.51%	2.60%	$0.91\%^{***}$
Transfer to Larger Firm	2.02%	1.34%	$0.68\%^{***}$
Transfer to Smaller Firm	1.35%	1.14%	$0.21\%^{***}$
Lease-Year Observations	118,612	724,524	
Panel B. Transfers from the Smallest 80% of firms			
Overall Transfer Probability	13.21%	9.90%	$3.31\%^{***}$
Transfer to Larger Firm	9.22%	6.14%	$3.07\%^{***}$
Transfer to Smaller Firm	3.38%	3.24%	0.14%
Lease-Year Observations	24,807	150,202	

2 Model Appendix

Insurance Requirements

A surety bond requirement changes the incentives of otherwise judgment-proof producers. Firms purchase surety bonds from insurers in a competitive market. These contracts obligate the insurer to pay the state if the insured firm leaves behind unpaid fines. Maximum payments are set by the coverage limit of the required bond, β, which is chosen by the state. Insurers sell surety bonds at a price π that just covers expected losses plus underwriting expenses,

$$\pi = \int_{y}^{\beta+y} [v(q,x) - y] f(v) dv + \int_{\beta+y}^{\bar{h}q} \beta f(v) dv + u \tag{6}$$

If damages are less than y, the insurer pays nothing. If damages are greater than y, the firm declares bankruptcy. It contributes its assets y towards environmental costs and the surety faces the remaining liability. The first term represents the insurer's losses when damages are between y and $\beta + y$. The second term represents the insurer's losses when damages exceed $\beta + y$, and the insurer pays β (so, unless the bond is set at or above worst-case damages, insurers also do not fully internalize expected damages). Underwriting expenses are u.

Surety bonds will be expensive for firms with few assets relative to their level of production. As y decreases, the probability that damages will exceed assets and the insurer will have to pay out increases. At the other extreme, the insurer will never pay out if the firm has assets greater than worst-case damages $\bar{h}q$, because the firm internalizes all possible environmental costs. In this case, the surety bond price will reflect only underwriting costs.

Insurers will also attempt to price contracts to incentivize safety effort. Unlike assets, safety effort (x) may not be fully observable. The insurer can adjust rates based on accident and regulatory compliance history, use credit reporting to punish firms that default, and/or demand collateral from outside the firm. These measures will induce firms to expend some safety effort, although this level of effort $\tilde{x}$ is likely to be below x^*. Since $\tilde{x} < x^*$, the equilibrium surety bond price will reflect a higher level of expected damages than under x^*.

The bond requirement causes intensive and extensive margin improvements. On the intensive margin, the bonded firm invests higher safety effort $(\tilde{x})$ than the unbonded firm because surety premiums increase internalization of environmental costs. This partially corrects the distortions shown in Figure 1, decreasing the height of Rectangle A and moving $\hat{\lambda}$ back towards $\hat{\lambda}^*$ and $\underline{\lambda}$ back towards $\underline{\lambda}^*$. On the extensive margin, firms with few assets relative to their potential environmental costs face high bond premiums. This leads to a desirable change in industry composition as financially weak producers (who have little incentive to operate safely) are screened out.

A bond requirement could also inefficiently exclude some firms. Underwriting or other transaction costs could increase bond prices above expected losses, potentially excluding some firms that would be profitable with full cost internalization and no transaction costs. I return to this topic in Section 7.

Capital Structure and Other Issues

The preceding sections do not address capital structure. One assumption is that firms cannot issue debt that is senior in repayment to accident damages. If so, any firm could eliminate liability exposure by issuing debt secured by all of the firm's assets, as in Che and Spier (2008). In the event of an accident, all assets would already be pledged to senior creditors. In the United States, this assumption is reasonable. For environmental costs in Texas oil and gas, the state has a lien against insolvent producers' assets that is senior to secured debt.[43] In other settings, it is difficult to foreclose on assets involved in environmental incidents, effectively subordinating a secured creditor's claim to environmental costs.[44]

When the firm is financed with debt, the owner's incentives to operate safely are reduced because some of the losses from accidents will be borne by creditors. Owners could seek to become highly leveraged in order to fully externalize the potential loss of y. However, as long as debt is junior to accident damages, borrowing costs for a firm with so little equity would be very high.

The model also treats firms as risk-neutral, so that there is no demand for liability insurance. If firms are risk-averse, this may not be true. However, firms only have incentive to purchase insurance for losses that they would bear. Firms have no incentive to purchase coverage in excess of their assets, so a voluntary insurance market does not solve the judgment-proof problem.

[43] Texas Natural Resources Code Section 89.083.

[44] For example, a creditor who acquires a Superfund site via foreclosure faces a risk of being held liable as an owner, although legal opinions differ (Harkins, 1994; Murray and Franco, 2011).

3 Data Appendix

I construct a novel dataset on market structure and environmental outcomes based on several administrative databases from the Railroad Commission of Texas (RRC), the state agency that regulates oil and gas production.

Operators and Production

Oil and gas production data come from the RRC Production Database Query (PDQ) dataset, which reports monthly crude oil and natural gas production at the lease level. Every lease is identified by a unique combination of district id, lease id, and oil or gas indicator. The dataset also identifies the unique operator number of the firm operating the lease each lease-month. There are 257,318 leases with at least one month of non-zero production during 1993–2012, and 35,568,267 lease-month observations. I include casinghead gas (natural gas from wells that primarily produce oil) in natural gas production. I include condensate (a liquid petroleum product from gas wells) in crude oil production.

Additional information on operators comes from the RRC Organization Report dataset. All firms involved in the production of oil or natural gas must file an organization report annually by the anniversary date of the firm's first filing. I successfully merge all but 4 lease-month observations (out of 40 million) from the PDQ dataset to the Organization Report dataset based on unique operator id numbers. This yields a dataset with 15,029 oil and gas producers with at least six months of non-zero production during 1993–2012. Because my focus is on the 2002 universal bond requirement, I further limit the dataset to firms with at least one month of production during the ten years surrounding the policy implementation year (March 1997 – February 2008). This leaves 10,489 operators.

An additional field identifies firms with related ownership (for example, name changes). Of the 10,489 operators, 1,175 are reported as being related to at least one other firm. In a robustness check in Appendix 1.1 I group related observations together into 9,888 firm groups and reproduce the main results. The results are extremely similar to those in the main text. I choose not to collapse related operators in the main results because it is not clear how to treat some operator-specific fields when collapsing. For example, if related operators have different assigned license renewal months, the analysis in Table 4 would require me to choose which renewal month to use for the collapsed firm group.

The organization report dataset includes each operator's initial filing date, most recent filing date, and assigned month of the year for license renewal. I define a firm's exit month as

12 months after its final license renewal. Specifically, I use 12 months after the assigned license renewal month. Thus, a firm with a final filing date of Dec. 15, 2000 and an assigned renewal month of January would have an exit month of January, 2002 (12 months after its January, 2001 license renewal). As a quality check, I compare the filing month to the assigned renewal month for each operator. 91% of filing dates are within three months of the assigned renewal month; 73% occur in the assigned month or the two previous months.[45] In the parts of the analysis where knowing the assigned license renewal month correctly is important (i.e., Figures 3–7 and Tables 1–4), I drop 899 operators (9%) with reported filing dates more than three months before or after their assigned license renewal month. For 136 operators (1%), assigned renewal months are not provided. For these 136 operators I assume the assigned renewal month is one month after the observed filing month, because this is the most common lag between filing and assigned renewal month in the data.

For Figure 3 only, I extend the sample back to 1990 (the earliest available year) by incorporating oil production data from the Final Oil and Gas Annuals (FOGA) datasets for 1990–1992. I do this because Figure 3 also addresses the 1991 partial bond requirement. The sample for that figure includes all operators appearing in either the FOGA or PDQ datasets. I confirm consistency of the FOGA and PDQ datasets by comparing FOGA and PDQ production reports for 1993 and 1994. For firms with final license renewal dates prior to 1994, I define exit month as 12 months after the final renewal filing.

Environmental Outcomes

Information on orphan wells comes from the RRC's publicly available Orphan Wells Database. I use the March 2014 version of the database. This dataset reports unplugged wells that have not produced for at least 12 months and for which the operator has not filed a license renewal in at least two years. It includes 6,314 orphan wells. The data include the well name, lease identifier, operator number, operator name, and the date of the operator's last P-5 license renewal. I successfully merge 100% of the orphan wells to the operator and production data based on unique operator numbers. The Orphan Wells Database is not a comprehensive list of wells ever orphaned, because some orphan wells have been plugged by the state. Because I am primarily interested in the rate of well orphaning before and after a policy change, an incomplete list does not affect my analysis as long as the state did not preferentially plug wells orphaned just before or just after the rules changes. There is no reason to suspect this.

[45]The insurance requirement was enforced according to the assigned renewal month, regardless of when firms filed their paperwork (as explained in the text).

Information on field rules violations come from the Railroad Commission's Severance Query Database. "Severance" is the RRC term for an enforcement action that shuts down production from a lease due to a rules violation. In the main analysis, I limit the data to severances for Field Rules Violations related to Statewide Rule 8 and Statewide Rule 14. Statewide Rule 8 governs water quality protection during drilling and production. Statewide Rule 14 requires that inactive wells be promptly plugged. This dataset contains the lease identifier, operator identifier, operator name, reason for the severance, date of warning letter, date of severance, and date the problem was resolved. I merge the severance data to the production data using unique operator identification numbers. I successfully merge 99.6% of Field Rule Violations since 1993. The final dataset includes 6,972 violations of Statewide Rule 8 and 5,318 violations of Statewide Rule 14.

Information on well blowouts comes from the RRC's list of blowouts and well control problems. This dataset contains the date of the incident, the name of the operator, and the name of the lease. The March, 2014 version of the list includes 522 blowouts since 1990. For 49% of the records, a unique drilling permit identifier number is reported. For these records, I merge to the drilling permit data, which includes unique operator numbers and allows a precise merge to the production and operator data. For another 34% of blowouts a lease identifier is reported that allows me to merge directly to the production data. For the remaining 16%, I attempt a "fuzzy" match based on on lease name and operator name. In total, I am able to match 96% of blowouts since 1990 with this combination of methods.

Additional Data

Data on operator-level bond choices were obtained through a public records request to the RRC. This dataset covers 1991–2012 and includes, at the operator-by-year level: the type of bond (surety bond, "Good Guy" option, etc.); the required bond amount; and the number and depth of wells.

Drilling data come from the RRC "Drilling Permit Master and Trailer" dataset. This dataset identifies all oil and gas wells drilled between 1991 and 2012. I follow Kellogg (2011) and Anderson et al. (2014) in working with the drilling data. The dataset identifies the date that each drilling permit was granted and, for wells that are completed, the date that the well began producing oil or gas. It also identifies spud-in dates (the date that drilling work began); however, as noted by Kellogg (2011), these dates are not reliably reported for a significant share of wells. I merge drilling permit data to the operator-level dataset based on unique operator numbers.