Drilling Like There's No Tomorrow: Bankruptcy, Insurance, and Environmental Risk

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Abstract

When liability is limited by bankruptcy, theory says that firms will take excessive environmental and public health risks. In the long run, this "judgment-proof problem" may increase the share of small producers, even when there are economies of scale. I use quasi-experimental variation in liability exposure to measure the effects of bankruptcy protection on industry structure and environmental outcomes in oil and gas extraction. Using firm-level data on the universe of Texas oil and gas producers, I examine the introduction of an insurance mandate that reduced firms' ability to avoid liability through bankruptcy. The policy was introduced via a quasi-randomized rollout, which allows me to cleanly identify its effects on industry structure. The insurance requirement pushed about 6% of producers out of the market immediately. The exiting firms were primarily small and were more likely to have poor environmental records. Among firms that remained in business, the bond requirement reduced oil production among the smallest 80% of firms by about 4% on average, which is consistent with increased internalization of environmental costs. Production by the largest 20% of firms, which account for the majority of total production, was unaffected. Finally, environmental outcomes, including those related to groundwater contamination, also improved sharply. These results suggest that incomplete internalization of environmental and safety costs due to bankruptcy protection is an important determinant of industry structure and safety effort in hazardous industries, with significant welfare consequences.

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1 Introduction

In almost all modern legal systems the debts of insolvent parties can be eliminated through bankruptcy. Bankruptcy protection benefits society by improving insolvent actors' work incentives and by mitigating coordination problems among creditors.[1] However, bankruptcy protection also distorts behavior by insulating actors from worst-case outcomes. For example, financial firms may become excessively leveraged, consumers may accumulate excessive personal debt, and governments may commit to unsustainable levels of public spending. A range of private contract features and public policies exist to combat this incentive problem, such as reserve requirements for banks, loan limits for consumers, and credit ratings for governments. These policies in turn affect many aspects of the economy.

One important implication of bankruptcy protection is that firms in hazardous industries will take excessive environmental and public health risks. In many countries, including the United States, accident liabilities and regulatory judgments can be discharged in bankruptcy. This limits firms' liability to their current assets, and thus decreases the safety incentives of firms with assets that are less than their worst-case liabilities. Economists call this the "judgment-proof problem" (Shavell, 1986). In addition to distorting short-run incentives, the judgment-proof problem may increase the share of small firms in the long run. Staying small allows firms to avoid the consequences of accidents, and therefore the need to invest in costly safety measures. The implication of the judgment-proof problem for society is too many harmful accidents. In addition, if there are economies of scale in production, the judgment-proof problem can inefficiently limit productivity.

This paper examines the effect of bankruptcy protection on market structure and environmental outcomes in the onshore oil and gas industry. This industry is an ideal setting for this analysis. Extracting crude oil and natural gas involves a risk of severe environmental and health damages through water pollution, toxic gas releases, and explosions. The industry in the United States includes many small firms. In 2012, almost 5,000 firms reported production in Texas alone (the largest oil and gas producing state, and the setting for my analysis). The vast majority of these firms had less than two million dollars in annual revenue.

In order to credibly measure the market structure impacts of the judgment-proof problem, the empirical analysis exploits quasi-experimental variation in the required surety bond amounts for oil and gas producers in Texas. Surety bonds are insurance contracts that obligate the insurer to pay the state for environmental costs left behind by bankrupt oil and gas producers. Bond mandates cause firms to internalize accident

[1] For a review of the economics of bankruptcy law, see White (2007).

risk through the premiums they pay to the insurer. Firms with poor safety records and financially weak firms with little incentive to exercise environmental care will face high premiums. Surety bonds are complicated by moral hazard, as I discuss later, but in general a bond requirement improves firms' safety incentives.

Texas introduced bond requirements for some oil and gas producers in 1991, and for all producers in 2001. For both policy changes, firms were required to comply with the new rules by the date of their annual operating license renewal. These license renewal dates are determined by the anniversary of a firm's first license application, and are thus distributed throughout the year. This quasi-random variation in the timing of the insurance requirements allows me to cleanly identify the effects of the policy. The analysis relies on a novel dataset of firm entry and exit, oil and gas production, and environmental outcomes for the universe of oil and gas producers in Texas, created by merging several different administrative datasets. Texas is the largest oil- and gas-producing state in the U.S. and keeps detailed records on production and environmental outcomes. Thus, it is an ideal geographic setting.

I find that greater internalization of environmental costs changed the industry structure. The 2001 universal bond mandate pushed about 6% of producers out of the market immediately. This was almost a 70% increase from the normal background rate of exit. The exiting firms were primarily small and were more likely to have poor environmental records. Finally, among firms that remained in business, the bond requirement reduced oil production among the smallest 80% of firms by about 4% on average, while production by the largest 20% of firms was unaffected. These results suggest that the ability to easily avoid environmental responsibilities prior to bonding inflated the number of small firms and their production.

Environmental outcomes also improved. After the universal bond requirement, the number of firms leaving their wells unplugged at the end of production (which creates a serious risk of groundwater pollution) decreased sharply. Well blowouts and violations of water protection rules also decreased substantially. These results suggest that by screening out firms with the least incentive to take care and increasing accountability for firms that remained in business, the bond requirement mitigated the harmful incentive effects created by bankruptcy protection.

The results of this study confirm the central predictions of a theoretical literature that previously has had little high-quality empirical validation. Existing empirical studies of liability and market structure are based on cross-sectional comparisons across states, industries, or firm sizes. This study departs from previous work by providing credible quasi-experimental evidence that the judgment-proof problem is an important determinant of industry structure and environmental outcomes in hazardous industries. In addition, the use of firm-level administrative microdata allows for much more detailed analysis than has been possible in previous work. For example, I am able to measure how firm-level output responds to insurance requirements. The results bolster concerns among economists and policymakers about judgment-proof issues in other sectors, including landfills, underground storage tanks, small-scale manufacturing, and hazardous materials transportation.

This study also makes a theoretical contribution by extending existing models of the judgment-proof problem to allow firms to vary in output. This formalizes the relationship between bankruptcy and industry structure. The model yields clear testable predictions about the effects of policy changes that mitigate the incentive problems created by bankruptcy, like the bond requirements that I observe in the empirical analysis.

Finally, this study contributes to our understanding of safety regulation in one of the most important industries in the world. Hydraulic fracturing has led to meteoric increases in oil and gas development in the United States in the past ten years. More than 15.3 million Americans have had an oil or gas well drilled within one mile of their home since 2000.[2] The shale boom has motivated a great deal of empirical research on outcomes of energy development such as environmental or wealth impacts (Allcott and Keniston, 2014; Darrah et al., 2014; Muehlenbachs et al., 2014). This study targets a different question that has not been as widely explored: Is society, through regulation, successful in inducing oil and gas producers to balance profits and environmental risk in a socially efficient way? This paper demonstrates one important reason that some firms depart from socially desirable behavior. The results also suggest that stricter and more widespread bond requirements would be likely to yield further benefits by causing producers to internalize a larger share of expected environmental costs.

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

2 Background

2.1 Liability and Industry Structure

The classic Shavell (1986) model of the judgment-proof problem shows that individuals whose potential liability exceeds their assets take inadequate care to prevent accidents

[2] Gold, Russel and Tom McGinty. "Energy Boom Puts Wells in America's Backyards." *Wall Street Journal.* October 25, 2013.

(*e.g.*, they drive their cars recklessly) and engage too often in activities that may harm others (*e.g.*, they drive too much). The same reasoning applies to firms in hazardous industries. Because safety effort is costly, firms that cannot be compelled to pay for accident damages will underinvest in accident prevention (Shavell, 2002). As I show in Section 3, they will also produce too much.

In industries where accidents and safety effort are expensive, the ability to avoid liability creates a cost advantage for financially weak firms. This means that firms may seek to strategically limit their asset exposure. One simple strategy is to keep the firm small.[3] Small firms have few assets to be seized after accidents. They can also be quickly dissolved in anticipation of accident claims, as in Boyd and Ingberman (2003). And, as I propose in Section 3, the probability that total accident damages will exceed total assets is larger when firms have fewer projects. Limiting firm size limits liability exposure, at the expense of economies of scale.

In the classic model of long-run competitive equilibrium, firm size is given by the unique output level that minimizes the U-shaped long-run average cost (LRAC) function (Viner, 1932). However, a large body of empirical research has documented disparities in firm size that are inconsistent with the Viner model (Bain, 1956; Bloom et al., 2012). More recent models seek to explain firm size more directly. In Lucas (1978), firms differ in "managerial technology." Better-managed firms are more productive and grow larger than poorly-managed firms, but span-of-control problems limit the growth of even the best-managed firms. In Banerjee and Duflo (2005), imperfect capital markets prevent all firms from adopting a capital-intensive technology with low per-unit production costs. The "missing middle" literature in development economics asks whether imposing regulations only on large firms keeps firms small (Rauch, 1991; Hsieh and Olken, 2014).

In industries with significant liability risk, bankruptcy protection may also affect firm size by creating an incentive to stay small. Surprisingly, formal models of the judgment-proof problem have had little to say about the choice of firm size. For example, Shavell (2002) assumes that firms produce only a single unit, and Pitchford (1995) describes firms as considering a single risky project.[4]

A few empirical studies have examined the judgment-proof problem. Alberini and Austin (2002) compares toxic releases in states with strict liability rules vs. negligence standards. They find that accidents are less likely in states with strict liability, except among the smallest firms. Ringleb and Wiggins (1990) argues that the number of small

[3]Other strategies include contracting out risky activities to small firms (Brooks, 2002); premature dissolution (Boyd and Ingberman, 2003); and financing with securitized debt that is senior to accident claims (Che and Spier, 2008). See LoPucki (1996) for a general review of these strategies.

[4]Similarly, 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.

firms in dangerous industries in the United States increased during the 1970's, at the same time that enforcement of liability for latent hazards like workplace carcinogen exposure became more aggressive. These and other existing empirical studies make cross-sectional comparisons across jurisdictions, firm sizes, or industries. These types of comparisons are vulnerable to omitted variables bias. For example, firm size may be correlated with experience or skill. In addition, data on firms and accidents are often only available at highly aggregated levels, which limits the detail of many analyses. There is an opportunity for highly credible quasi-experimental approaches using detailed, firm-level data to provide evidence on how bankruptcy protection affects industry structure and safety effort.

2.2 Effects of An Insurance Mandate

One widely-used policy to mitigate the judgment-proof problem is to require firms to have liability insurance or bonds.[5] Firms comply with bond requirements either by depositing valuable assets with the regulator, to be returned once production is completed safely; or by purchasing a surety bond from an insurer. Surety bonds are a promise by 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.[6] Firms with few assets typically choose surety bonds instead of cash bonds.

Insurance and bond requirements are commonplace. 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.[7] In construction, contractors must purchase bonds that will pay for project completion if they go out of business. Bonds or liability insurance are also required for owners of landfills and underground chemical storage tanks, both of which can cause serious pollution problems. In oil and gas extraction, all of the major oil- and gas-producing states and the federal Bureau of Land Management require bonds, although in many cases they are very small relative to potential damages.

Insurance and bond requirements mitigate the judgment-proof problem because firms internalize accident costs through premiums. Depending on how well insurers can observe safety effort, these policies have both intensive- and extensive-margin benefits. If effort is observable, then premiums will be conditioned on effort, the firm internalizes the full expected costs of accidents, and safety effort and industry structure will both

[5]Other responses include direct regulation of safety (Shavell, 1984) and the extension of liability to firms' business partners Kornhauser (1982); Pitchford (1995); Boyd and Ingberman (2003).

[6]Bond requirements often allow firms to purchase true surety bonds (from insurers) or irrevocable letters of credit (from banks). These instruments are very similar, and I follow the convention established by regulators of referring to both as "surety bonds" or "bonds".

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

be socially optimal. In the opposite extreme where safety effort is completely unobservable, the benefits are all along the extensive margin. Mandated insurance changes industry structure but not safety effort. Firms exercise the same safety effort as in the absence of the requirement,[8] and pay insurance premiums that reflect expected damages contingent on this sub-optimal level of safety effort. Insurance premiums act like a tax that discourages participation in the activity, screening out some firms whose revenues before the policy exceeded private but not social costs (Polborn, 1998).

Using state-level panel data on 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. This cross-sectional evidence suggests that insurance mandates can improve environmental outcomes. However, the highly aggregated data limits conclusions about firm-level responses or industry composition.

3 Model

This section proposes a model of how bankruptcy protection leads small firms to undervalue safety, and leads to too many small firms. It extends the Shavell (1986) model to allow for endogenous selection of firm size and output. Previous models of judgment-proof firms treat output or the number of projects as constant across firms, which ignores the stylized fact that small producers are more likely than large producers to be judgment-proof. I use the model to show how the judgment-proof problem inefficiently raises the number of small producers, and leads each of the judgment-proof firms to produce more than is efficient while exerting less-than-efficient safety effort. I also show how bond requirements partially mitigate this market failure. In addition to formalizing the relationship between industry structure and liability, the model yields a clear set of theoretical predictions to take to the data.

3.1 Profit Maximization in a Hazardous Industry

A homogeneous good is produced by risk-neutral firms in a competitive industry. Production may cause accidents that harm others. When an accident occurs, the damages are a constant h. Firms can reduce the likelihood of accidents by exerting costly safety effort. The level of safety effort is a continuous variable x, and the cost is normalized to one, so that expenditures on safety are also x. The probability that an accident will occur for any given unit of production is $\gamma(x)$, which is decreasing in x. When an accident occurs, a fine equal to h is levied.

Accident risk and safety effort increase linearly per unit of output (q). For example,

[8] In fact, Shavell (2005) shows that safety effort decreases since insurance premiums reduce the firm's assets and thus its liability exposure.

each additional oil well or manufacturing plant presents a hazard and requires independent safety effort.[9] The function $f(v; q, x)$ is the probability distribution of total accident damages v for a firm. Damages are bounded by hq (*i.e.*, an accident with every unit of production). I assume that accidents are independent, so $E[v] = \gamma(x)qh$.

A firm chooses q and x to maximize the profit function,

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

Profit-maximizing safety effort x^* minimizes effort costs plus fines: $q[1 + \gamma'(x^*)h] = 0$. At x^*, the reduction in expected fines from increased safety effort equals the marginal cost, which is one. Profit-maximizing output q^* equates marginal cost, including safety effort and expected fines, with price: $p = c'(q^*)+x^*+\gamma(x^*)h$. Firms internalize accident costs through fines, so (x^*, q^*) is also socially optimal.

3.2 The Judgment-Proof Problem With Output Choice

This section introduces a parameter y, which is the assets owned by the firm 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. The profit function becomes,

$$pq - c(q) - xq - \begin{cases} \gamma(x)qh & y \geq hq \\ \left[\int_0^y vf(v; q, x)dv + \int_y^{hq} yf(v; q, x)dv\right] & y < hq \end{cases} \tag{2}$$

When y is greater than or equal to maximum possible liability, the profit function is unchanged. However, when y is less than maximum possible liability, the firm will not consider the full expected costs of accidents. Instead, it considers the mean of a truncated damage distribution, valuing damage outcomes greater than y at y. Expected damages are replaced in the profit function by the probability-weighted sum of damages from zero to y, plus y for all larger damage outcomes.[10]

A firm with $y < hq$ is, to some degree, judgment-proof. For at least some realizations of total damages, the firm's assets will be less than the damages. It chooses safety effort $x(y) < x^*$, increasing the risk of accidents. The intuition is simple. The benefit of accident prevention is smaller for a judgment-proof firm than a responsible firm because the judgment-proof firm does not internalize the full expected cost of accidents.

Judgment-proof firms also choose $q(y) > q^*$. Again, the reasoning is straightforward.

[9] A more complex model could also include fixed costs of safety. The primary implication would be that only firms above some minimum efficient scale would find it profitable to invest in safety, reinforcing the judgment proof problem.

[10] When accidents are independent, the number of accidents follows a binomial distribution, and expected fines for the judgment-proof firm can be expressed more precisely as,
$\sum_{k=0}^{\frac{y}{h}} kh\phi(k) + \sum_{k=y/h}^{q} y\phi(k)$ where $\phi(k)$ is the binomial pmf, $\binom{q}{k}\gamma(x)^k(1-\gamma(x))^{q-k}$.

If the firm fully internalized accident costs, the safety cost of another unit of output would be the cost of socially optimal safety effort plus expected accident damages at that effort level: $x^* + \gamma(x^*)h$. For a judgment-proof firm starting from the same level of output, the safety cost of another unit of output is the cost of suboptimal safety effort plus the change in the expected private cost of total accident damages. This is $x(y) + A$, where $A = \frac{d}{dq}[\int_0^y vf(v;q,x)dv + \int_y^{hq} yf(v;q,x)dv]$. It was already established that $x(y) < x^*$. It is also clear that $A < \gamma(x^*)h$, because for damage realizations greater than y, the firm will not bear the additional damages imposed by this unit; and both firms face identical damages when damages are less than y.[11] So, marginal private safety costs are smaller when firms are judgment-proof, leading to higher production compared to a same-sized firm that was responsible for all damages.

3.3 The Judgement-Proof Problem and the Size Distribution of Firms

This section shows how the judgment-proof problem increases the number of small firms. This requires some additional assumptions. I assume heterogeneity between firms in technology, represented by θ. A firm's production cost for quantity q, exclusive of safety effort and fines, is given by $c(q;\theta)$. Firms with larger θ have higher fixed costs, but lower minimum average cost. This feature of the model can be motivated in several ways, as discussed in Section 2.1. For example, in the Lucas (1978) model of firm size, larger θ would correspond to more skilled management.

Secondly, I assume that small firms are more likely to have assets less than total damages. This assumption is widely made in the accident economics literature, but is not often tied to a formal economic model. One way to motivate this feature is to assume that y increases linearly in q (for example, because every well or plant adds valuable physical assets). In that case, the volatility of total damages relative to mean damages (*i.e.*, the coefficient of variation) decreases in q. A firm with many plants is less likely to have accidents at all of its plants than a firm with one plant, when accidents are independent. So, the probability that accidents will bankrupt larger firms is lower because pooling projects reduces the variability of total damages.[12] A second motivation for this assumption is that it is easier for small firms to pursue a "fly-by-night" strategy of premature dissolution, as in Boyd and Ingberman (2003). It is less costly for firms with few assets to quickly strip value out of the firm in anticipation of liability claims for accident damages.

Figure 1 shows the potential for inefficient market structure. The thick solid curves show long-run average cost curves for two types of firms with different θ, when firms

[11] The privately-optimal x for the judgment-proof firm may also increase with q. However, re-optimizing x can only reduce marginal cost relative to the old x.

[12] Technically, this requires the additional assumption that y is at least as large as expected per-unit damages under socially optimal safety effort. If accidents are rare, this assumption is not restrictive.

fully internalize expected accident damages. These curves represent the vertical sum of average production costs, $ac(q;\theta)$, and average safety costs (effort plus expected damages), $x^* + \gamma(x^*)h$. Because $\theta_2 > \theta_1$, the minimum average cost for Type 2 firms is below and to the right of that of Type 1. When firms internalize accident damages, large firms are most privately efficient and will dominate in a competitive market setting.

The dashed curves show how bankruptcy lowers private average costs for small firms. When q is small, the firm is unlikely to pay the full costs of accident damages because damages are likely to exceed assets. It chooses a low level of safety effort, and its overall safety costs, shown by the dashed safety cost curve at the bottom of the figure, are low. As q increases, the share of expected damages internalized by the firm increases, so that per-unit safety costs approach $x^* + \gamma(x^*)h$. The dashed average cost curve shows overall average cost for Type 1 firms when bankruptcy limits liability. Now small firms are the most privately efficient and will dominate in a competitive market setting.[13]

This model demonstrates a tradeoff between economies of scale and the ability to avoid accident costs. For Type 2 firms, economies of scale are large. These firms maximize profit by producing a large amount of output, even though this large firm size means they must fully internalize the expected costs of accidents. Type 1 firms are small enough to avoid some accident costs, but economies of scale are limited. These types are two examples from a range of possible firm sizes that depends on the management or other technologies available in the market. The privately optimal firm size balances avoided liability and economies of scale.

What are the welfare effects of the judgment-proof problem? The per-unit social cost of the judgment-proof firm's production is higher than under full cost internalization. This is because, by definition, safety effort x^* minimizes the sum of effort costs and accident costs. Any other level of safety effort results in higher total social costs. The marginal unit of production by judgment-proof firms has negative net benefits due to suboptimal safety effort and excessive production. In addition to this externality problem, if output produced by judgment-proof firms would otherwise have been produced by large firms, there are also foregone economies of scale.

3.4 Alternative Assumptions

It is worth briefly considering some of the assumptions in the previous sections. The model ignores other well-known problems with liability regulation. For example, it

[13] In this simple model, a single type of firm will dominate the market in equilibrium. In reality, without infinite potential entry of each type, there would be a range of firm sizes in the market. However, which type was most privately efficient would still be determined by the reasoning here, so that bankruptcy protection would increase the number of small firms.

assumes that accidents are always detected and that penalties exactly equal social damages. A complete model of liability regulation would include these features and several others described in Shavell (2007) and related works. I have abstracted away from these issues to focus on the judgment-proof problem. Adding these features to the model would not fundamentally change the predictions.

The model also treats firms as risk-neutral, so that there is no private demand for liability insurance. If firms are risk-averse, this may not be true. However, note that firms only have incentive to purchase insurance for losses that they would otherwise pay. Judgment-proof producers have no incentive to purchase coverage in excess of their assets, so the existence of a private insurance market is insufficient to eliminate the judgment-proof problem.

The preceding section also does not address capital structure. One implicit assumption is that firms cannot issue debt that is senior in repayment to accident damages. If this were possible, firms of any size 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. For environmental damages in the United States, the assumption that this is impossible mirrors reality. Several federal and state laws make it difficult for lenders to foreclose on assets involved in environmental incidents, effectively subordinating a secured creditor's claim to environmental costs.[14] In the specific case of Texas oil and gas extraction, for certain types of clean-up costs the state has a lien against insolvent producers' assets that is senior to secured debt.[15]

When the firm is financed with debt, the owner's incentives to operate safely are reduced because some of the losses due to accidents will be borne by creditors. This raises the question of why firm owners in hazardous industries do not seek to become highly leveraged in order to fully externalize the potential loss of y. The answer is that, as long as debt is junior to accident damages, borrowing costs for a firm with this strategy would be very high because lenders would fear losses.

Finally, for the application to oil and gas extraction, it is worth considering how to treat site reclamation in the model. Plugging wells and remediating waste storage pits is an important investment of safety effort that reduces groundwater contamination. In practice, regulators do not only use a liability rule to regulate reclamation. Instead, reclamation is mandated at all sites. For this element of safety effort, penalties to the firm are a deterministic function of effort. Firms pay fines with probability 0 if they remediate and probability 1 if they do not. What matters is that small firms can avoid

[14] Interpretations of the law have varied, but, for example, a creditor who takes ownership of a Superfund site through foreclosure faces a non-trivial legal risk of being held liable as an owner (Harkins, 1994; Murray and Franco, 2011).

[15] Texas Natural Resources Code Section 89.083.

both liability-based penalties and effort-based penalties through bankruptcy.

3.5 Insurance Requirements Mitigate the Judgment-Proof Problem

This section shows how a surety bond requirement leads small producers to internalize a larger share of damages. Bonding increases care and reduces participation by judgment-proof firms. I also discuss how setting the bond amount too high can limit participation by firms whose operation would be welfare-improving.

Firms purchase surety bonds from insurers. These are contracts that obligate the insurer to pay the state any positive difference between the firm's damages and its assets. Maximum payments by the surety are limited by the face value of the required bond, β, which is chosen by the state. In a competitive market, insurers sell surety bonds at a price π that just covers expected losses plus underwriting expenses.

$$\pi = \int_{y}^{\beta+y} (w - l) f(v) dv + \int_{\beta+y}^{hq} (\beta - l) f(v) dv + u \tag{3}$$

The amount by which damages exceed the firm's assets is $w = \max[0, v(q; x) - y]$. Collateral required by the insurer is l. If damages are less than y, the insurer pays nothing. The first integral term represents the insurer's losses when damages are between y and $\beta + y$, so that the insurer pays the full difference between damages and assets. The second integral represents the insurer's losses when damages exceed $\beta + y$, so that the insurer pays β (so, unless the bond is set at or above worst-case damages, insurers do not fully internalize expected damages). Underwriting expenses are u.

A surety bond does not directly increase a firm's liability exposure. Damages greater than y are paid by the insurer, not the firm, so that there is moral hazard on the part of the firm. However, the insurer will screen clients and design contracts to limit losses. Insurers can directly monitor safety effort, adjust rates based on assets or accident history, use credit reporting to punish firms who default, and/or demand collateral (sometimes from outside the business). These measures will induce firms to expend some safety effort, although this level of effort $\hat{x}$ is likely to be below x^*. Since $\hat{x} < x^*$, the equilibrium surety bond price will reflect a higher level of expected damages than under x^*.

The surety bond requirement also introduces transaction costs, which are borne by the firm. I assume that collateral is invested at a rate lower than the firm's opportunity cost of capital, with the proceeds accruing to the firm. Collateral requirements cost the firm lr, where r is the difference between the firm's opportunity cost of capital and the rate at which collateral is invested. Underwriting costs u are also borne by firms.

For a bond amount equal to β, a small firm's expected profit is,

$$p\hat{q} - c(\hat{q};\theta) - \hat{x}\hat{q} - \int_0^y vf(v)dv - \int_y^{hq} yf(v)dv - lr - \pi(\hat{x},\hat{q},y) \tag{4}$$

The bond requirement causes intensive and extensive margin improvements. On the intensive margin, the bonded firm invests higher safety effort ($\hat{x}$) and produces less ($\hat{q}$) than the unbonded firm because surety premiums improve incentives. On the extensive margin, firms with few recoverable assets will face high bond premiums, since insurers know it is not in those firms' private interest to exercise adequate safety effort. This leads to a desirable change in industry structure as financially weak producers are screened out.

A bond requirement may also exclude firms whose operations would be socially efficient. Underwriting and collateral costs increase bond prices above expected losses, potentially excluding some firms that would be barely profitable with full cost internalization and no transaction costs. Other potential inefficiencies in insurance markets could also result in coverage not being available to responsible firms. I return to this topic in Section 6.

3.6 Testable Predictions

This model makes several testable predictions about policy changes that reduce the ability to avoid bankruptcy in industries with large potential liabilities. There should be exit by small producers, as firms that had been privately profitable but not socially efficient are pushed out of the market. These exiters should have had more accidents prior to the policy change than firms that stay in the industry. Small firms that remain in the market should decrease their output as they internalize a larger share of marginal safety costs. Finally, environmental incidents should decrease due to increased safety effort per unit of production.

4 Empirical Analysis and Data

The setting for the empirical analysis is the onshore oil and gas extraction industry in Texas. This is an excellent industry in which to study liability and bankruptcy. There are significant environmental risks and many small producers. Firms produce homogeneous products, and the industry is essentially perfectly competitive due to extremely liquid international markets. Finally, the size of the industry means that environmental incidents occur frequently enough to allow for detailed empirical analysis. Texas is the largest producer among the United States and keeps detailed data on production and accidents, making it an ideal geographic setting.

4.1 Environmental Protection in Oil & Gas Extraction

Oil and gas extraction poses potential risks of water pollution, methane leaks, and releases of toxic gases and radioactive materials. Historically, water pollution has been considered the most serious risk. Crude oil, drilling chemicals, and saltwater produced along with oil and gas can all have severe health and natural resource impacts.

Extracting crude oil and natural gas involves drilling and production phases. Wells are drilled into underground formations thought to contain hydrocarbons. Successful wells will produce for twenty years or more, with declining production over time. Water contamination is a serious concern during both drilling and production.

During drilling, a cement and steel well casing is constructed around the well bore. Correct construction of this casing is important to prevent leaks into groundwater. In addition, open pits for temporary storage of drilling wastes must be carefully sited and constructed. Finally, if drillers lose control of well pressure, there may be a "blowout", possibly spreading oil or drilling fluids over a wide area. Blowouts can also cause fires, equipment losses, and injuries or deaths. If a blowout damages the underground resource, nearby mineral owners can claim damages. The total costs of a well blowout can be tens of millions of dollars (Jones, 2003).[16]

During production, crude oil or liquid wastes can leak from storage tanks, pits, pipelines, or trucks. In addition, degraded well casings can develop leaks into groundwater. Producers must monitor the integrity of aging wells. Once wells are no longer producing (or leaks are detected), they should be plugged with cement below groundwater depth. Plugging wells costs thousands of dollars per well, so operators have an incentive to avoid or delay it. In the extreme, wells may remain unplugged after the firm is dissolved. These "orphan wells" must be plugged with public funds. Because operators may hold inactive wells for years before exiting, and because state agencies have limited budgets, state-funded plugging may come too late to prevent groundwater contamination. Between 1983 and 2008, orphan wells caused 17% of detected oil and gas groundwater contamination incidents in Texas, and 22% in Ohio (Kell, 2011).[17]

[16] Because a firm's demand for drilling services varies greatly in time and space, drilling is typically carried out by specialized contractors. Well owners and drillers negotiate the legal responsibility for accidents as part of their contracts. Typical contracts, such as the model contracts provided by the International Association of Drilling Contractors, assign most liability to well owners. Ultimately, both firms face some liability exposure, since the indemnities in these contracts are imperfectly enforceable. For example, either firm could become a target for liability claims if the counterparty became insolvent (Anderson, 1989; Jones, 2003).

[17] 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

4.2 Changes in Insurance Requirements

Credibly measuring the effects of the judgment-proof problem requires variation in firms' ability to avoid liability that is exogenous with respect to unobserved determinants of the outcome of interest. This is a difficult empirical challenge. A randomized control trial assigning asset levels or bond requirements to firms is unlikely to prove feasible. Cross-sectional comparisons of large vs. small firms, or across industries or jurisdictions, are highly vulnerable to omitted variables bias. For example, deep-pocketed producers may be more experienced or more skilled than financially weak producers.

This paper exploits variation over time in bond requirements. Stricter bond requirements reduce small firms' ability to escape environmental costs. Texas introduced a bond requirement for some oil and gas producers in 1991 and extended it to all producers in 2001. Both of these policy changes 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 detail in Section 5, this variation allows me to separate the effects of the policy changes from other time-varying determinants of industry composition.

Senate Bill 1103 in 1991 first introduced the bond requirement, but it required bonds for only some producers. Firms with an acceptable compliance history could instead pay a small annual fee called the "Good Guy Fee."[18] 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 January, 2002. I focus the analysis primarily on the 2001 change because prior to this, few firms were bonded.[19]

Under both the partial and the universal bond requirements, the bond amount depended on the number and depth of wells. The formula was $2 per foot of well depth across all wells. The mean depth of existing wells in 2001 was 3,300 feet.[20] 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.[21]

40% from drilling and well completion.

[18] Firms with a four-year record of compliance with Commission regulations could pay the $100 per year 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 1991 law also introduced a $100 annual fee for each inactive, unplugged well.

[19] S.B. 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.

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

[21] Between steps in the blanket bond schedule – at 10 to 11 wells and 99 to 100 wells – 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

Ninety-seven percent of bonded producers chose to purchase a bond from an insurer instead of posting their own assets as a cash bond.[22] 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%. Bond issuers may also require collateral from firms deemed to be high risk (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 five wells might pay $330 per year in bond premiums, while a high-risk operator with the same number of wells might pay $2,475 per year while also facing collateral requirements.[23]

The importance of the bond requirement to producers' costs was reflected in the widespread 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."[24] 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."[25]

The policy was primarily intended to reduce orphan wells, but the required bonds were conditioned on preventing all types of water pollution. The bond 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."[26] 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 surety.

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risk exposure and so should have increased premiums for a given level of coverage. Second, bond costs were small for low-risk firms. Ignoring premium increases, a large firm acquiring a low-risk five-well firm would have saved about $165 per year for each of the firms' owners, following the example calculation in the following paragraph. These savings were likely small compared to other benefits and costs of merging. For high-risk firms, the benefits of combining with a large producer with a good reputation were higher. But the main reason for the savings was not the blanket bond; it was that the larger firm was a better insurance risk.

[22] This is the share of bonded license renewals from 2002-2005 with surety bonds or letters of credit.

[23] Low risk firm: 3,300 feet * 5 wells * 2%. High-risk firm: 3,300 feet * 5 wells * 15%.

[24] "PBPA members detailing problems getting bonds." *Midland Reporter Telegram.* March 31, 2002.

[25] "Can't Afford the Bond? Then Don't Run a Well." *San Antonio Express News.* August 9, 2002.

[26] Railroad Commission of Texas Blanket Performance Bond P-5PB(2). http://www.rrc.state.tx.us

4.3 Data

For this analysis, I construct a novel dataset on market structure and environmental outcomes. The core of the analysis relies on several administrative datasets from the Railroad Commission of Texas (RRC), the agency that regulates oil and gas production. Operator entry and exit dates come from the RRC "Organization Report" dataset. All operators must file an organization report annually by the anniversary date of the firm's first filing. I define a firm's exit date as 365 days after its final organization report renewal, since the firm chose not to renew its operating license as of this date.

Bond data were obtained through a public records request to the RRC. This dataset includes, each year for every operator: the type of bond (surety bond, "Good Guy" option, etc.); the required bond amount; and the number and depth of wells.

Oil and gas production data come from the RRC Production Database Query (PDQ) dataset (for 1993–2010) and the RRC Final Oil and Gas Annuals (FOGA) dataset (for 1990–1992). Both datasets report monthly crude oil and natural gas production at the lease level.[27] A lease is a parcel of land on which the producer has negotiated the right to explore for oil and gas, and may contain multiple wells. Each lease-month observation is matched to an operator using unique operator identification numbers.

Drilling data come from the RRC "Drilling Permit Master and Trailer" dataset. That dataset identifies "spud-in" and well completion dates for every well drilled between 1991 and 2010. Spud-in is the date that drilling began, and well completion is the date that the well first produced oil or gas, which coincides with the conclusion of rig work.[28] Wells are matched to operators using the same operator identification numbers.

Environmental outcomes comes from several datasets. Orphan well data come from the RRC Orphan Well Database. This is a snapshot of orphan wells that have not yet been plugged by the state as of March 14, 2014.[29] Information on environmental rules violations comes from the RRC's online Severance Query Database. I am primarily interested in violations of Statewide Rules 8 and 14. Statewide Rule 8 ("Water Protection") governs water quality protection during drilling and production. Statewide

[27] I include casinghead gas (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. In practice, condensate is a slightly different product and its market price can differ slightly. However, it is a small share of total production, and excluding condensate does not meaningfully affect the results.

[28] The data extend back to 1976; however, Kellogg (2011) reports that spud-in dates were not reliably recorded prior to 1991. Also following Kellogg (2011), I disregard completion dates for wells with reported drilling times less than 0 or greater than 180 days. For wells with no valid completion date, I assume that rig work took place for the average drilling time of 20 days.

[29] A comprehensive list of all wells that have ever been orphaned is not available from the RRC. Because I am primarily interested in the change in the rate of well orphaning with bond policy changes, an incomplete list does not affect my analysis as long as the state did not preferentially plug wells orphaned just before or just after rules changes.

Rule 14 ("Plugging") requires that inactive wells be plugged promptly. Information on well blowouts comes from the RRC "Blowouts and Well Control Problems" list. Oil and gas operators are required to notify the Commission of all well blowouts. Orphan wells and rules violations are merged to operators using operator identification numbers. The blowout data do not include these numbers. I match blowouts to operators using unique lease identification numbers where provided. For the remaining blowouts, I carefully match on lease name and operator name.

The final dataset includes all operators in the state with positive oil or gas production between 1990 and 2010. This includes 17,672 firms.

4.4 Descriptive Evidence of the Judgment-Proof Problem

Before proceeding to the empirical results, this section summarizes descriptive evidence that suggests the judgment-proof problem may have been important in this industry. In 2001, the year before the expanded bonding requirement took effect, 5,302 firms in Texas reported oil and gas production. Figure 2 shows the distribution of their revenues. Above $15 million, the horizontal axis is truncated to show the five largest producers. The vertical axis shows the number of firms in each 1 million dollar bin. While the largest firms produced over one billion dollars worth of oil and gas, most firms had revenues below $1 million. Table 1 lists the quintiles of the revenue distribution. The 80th percentile of the revenue distribution is only $1.4 million dollars, and the 20th percentile is $33,000.

Figure 3 shows that environmental incidents were concentrated among small operators. I calculate average annual production for all firms from 1990–2001. The x-axis shows the sum of annual production across all firms. Producers are ordered left to right along this axis from smallest to largest. The vertical axis shows the cumulative share of environmental incidents. Almost 100% of orphan wells, 95% of field rules violations, and 40% of well blowouts are associated with the 20% of total production that comes from the smallest firms.

Finally, there is also evidence of high bankruptcy rates. According to a 2003 report by the State Review of Oil and Natural Gas Environmental Regulations (STRONGER), during 2001 and 2002 (before the bond requirement was fully implemented), the state was unable to collect 68% of the penalties assessed for oil and gas rules violations. The most common reason that these fines were uncollectible was bankruptcy.[30]

[30] "The 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).

5 Results

There are three sets of emprical analyses related to industry composition, firm-level output, and environmental outcomes. This section presents the results of each. As discussed in Section 4.2, I focus the empirical analysis primarily on the introduction of the universal bond requirement in 2001, because prior to this many producers were able to avoid bonding through non-bond alternatives like the "Good Guy Option."

5.1 Industry Composition

The model in Section 3 predicts that increased bond requirements will cause some firms to exit because they are no longer profitable after internalizing a larger share of environmental costs. I measure the effect of the 2001 bond requirement on producer exit using a regression discontinuity (RD) design. This design takes advantage of the twelve-month bond rollout by comparing firms who renewed within a narrow window in time around the implementation of the policy.[31] I run the regression,

$$1[Exit]_{it} = \alpha + \beta_1 1[Begin\ Rollout]_t + \beta_2 1[End\ Rollout]_t + \beta_3 T_t + X_t \beta_4 + \psi_m + \eta_{it} \quad (5)$$

The dependent variable $1[Exit]_{it}$ is an indicator variable equal to one if firm i exits in month t. I observe exit decisions once per year per firm, during the firm's renewal month. Thus, while the analysis is at the monthly level, there is one observation per firm per year. After firms exit they are removed from the sample. $1[Begin\ Rollout]_t$ is an indicator variable equal to one in January 2002 and all later months. $1[End\ Rollout]_t$ is an indicator variable equal to one in January 2003 and all later months. T_t is a local polynomial in the running variable, the number of months before or after January 2002. X_t includes monthly crude oil prices.[32] ψ_m is a set of month-of-year fixed effects. 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 oil and gas prices. The constant term α gives the background level of exit prior to the policy change. T_t is centered at January, 2002 and oil and gas prices are centered at their sample means, so α gives the level of exit that would have been expected immediately prior to the policy change, under average oil and gas prices (and in January when month-of-year fixed effects are included).

The error term η_{it} includes unobserved determinants of $1[Exit]_{it}$. The identifying assumption in this analysis is that η_{it} does not change discontinuously at the im-

[31] As suggested in Lee and Card (2008) for RD designs with discrete support, I cluster the standard errors according to the running variable. The running variable is month; I cluster by quarter.

[32] 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. Appendix Table 2 shows results controlling for oil and natural gas separately.

plementation threshold. Under this assumption, the bond rollout allows for clean measurement of β_1 by comparing exit during a small number of months after implementation to exit during a small number of months prior to implementation. As I show below, this identifying assumption is bolstered by the pattern of exit observed at the beginning and end of the bond rollouts in 1991 and 2002. There are clear, symmetric discontinuous changes at each of these thresholds. Thus, it unlikely that the increased exit at the time of the policy change was solely driven by an unobserved idiosyncratic shock.

5.1.1 Industry Composition: Graphical Results

Figure 4 shows the raw data on producer 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 firms exited each month. With the bond requirement, the rate of exit increases sharply to over 100 firms per month and stays high for 12 months. After the 12 months, the level of exit decreases sharply. The same pattern of sharply increased exit for twelve months accompanies the implementation of the universal bond requirement in 2002. In 2002, the level of exit approximately doubles from about 60 to about 120 firms per month. Appendix Figure 1 shows a similar figure for net entry (entry minus exit) by month. The pattern is very similar.

Figure 5 shows a graphical version of the RD estimator for the 2001 universal bond requirement. The sample includes 1997–2006. The x-axis shows months before and after January 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 fit for 1997–2001, a separate linear fit for 2002, and a separate quadratic polynomial fit for 2003–2006. There is a clear increase of about five percentage points in the share of firms exiting in January, 2002. At the end of the twelve-month implementation period, there is a discontinuous decrease in exit to approximately the pre-implementation level. There is also a slight upward trend in exit for about 18 months before January 2002. This upward trend may reflect the effect of unrelated Railroad Commission rules in 2000 that increased costs for firms with many inactive wells.[33] The last six months could also include anticipatory exit after passage of the law, for example because capital investments needed to continue operations were no longer economic. However, the effect of the universal bond requirement in January, 2002 is visually obvious in the discontinuous increase in exit in that month.

Figure 6 shows the same figure, by quintile of firm-level average annual oil and gas production. These quintiles are defined based on average production during 1996–2007

[33] See *Texas Register* Volume 25 page 9924 describing changes to the "W1-X" plugging extension program for inactive wells implemented in November 2000.

in barrel of oil equivalents (BOE).[34] The effect of the universal 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 January 2002. In the second quintile, the effect is about 10%; in the third, it is about 5%, and in the fourth it is about 4%. In each of these middle quintiles the effect is growing smaller, but is clearly visually distinguishable in every case. In contrast, in the top quintile of firm size there is no distinguishable change in the share of firms exiting in January 2002.

For robustness, Appendix Figure 2 shows the number of firms with license renewal dates in each month of the sample. These dates are assigned by the RRC and cannot be manipulated by firms. The bond requirement was implemented according to firms' assigned renewal dates, so firms could not avoid it by submitting their renewal paperwork early. If such manipulation had been possible, it may have introduced systematic differences between firms up for renewal before and after implementation. As expected given the implementation rules, however, the number of firms up for renewal is smooth across the implementation threshold.

5.1.2 Industry Composition: Estimation

Table 2 shows regression results for equation 5. As in Figure 5, each specification includes a quadratic polynomial in time for 1997–2001; a separate linear polynomial for 2002; and a separate quadratic polynomial for 2003–2007. In Column (1), the implementation of the expanded bonding rule causes a discontinuous increase in exit of 6.8 percentage points. This means that an additional 6.8% of the firms scheduled to renew their license each month chose to leave. Over 12 months, this effect would decrease the total number of firms in the industry by 6.8%. The baseline rate of exit before the policy change, given by the constant term, is 9%. The specification in Column (2) controls for crude oil prices in each firm's assigned renewal month. This decreases the estimated effect of the bond policy slightly to 6.3 percentage points. The effects of price increases on exit are negative, as expected. Oil prices are centered at their mean value in the panel, so the constant term in Column (2) describes the baseline exit rate at average oil and gas prices. Finally, the specification in Column (3) also includes calendar month 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.

These results suggest that the bonding requirement caused 6% of the firms in the industry to exit immediately. This is about a 65% increase from the normal rate of

[34] 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. Results are similar if I use value of production instead of BOE; however, BOE is preferred because changes in oil and gas prices over time affect the production value measure.

exit. To further contextualize this effect, it is interesting to compare the exit due to the bond mandate with the amount of exit caused by month-to-month fluctuations in output prices. The spot price of crude oil is one of the best predictors of future oil prices, even compared to futures prices (Alquist and Kilian, 2010). Thus, by reducing expected future revenue for producers, output price decreases play a similar role to generic cost shocks. Taking literally the estimates in Column (3) of Table 2, a $10 decrease in the crude oil price would lead to a 0.5 percentage point increase in exit probability across all firms. So, the immediate contraction caused by bonding is about 12 times larger than the exit caused by a $10 decrease in the world oil price.[35]

Table 3 presents regression results according to firm size. Again, the results are consistent with the graphical evidence in Figure 6. The output quintiles are the same as in the figure. The specification in each column matches Column (3) in Table 2. The effect of the bond requirement is decreasing monotonically in firm size. In the first and second quintiles exit increases by about 12%, while in the third and fourth quintiles it increases by about 5%. 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 the bottom four quintiles, from 17% in the bottom quintile to 5%. The baseline level of exit for large producers is 9.7%. This relatively high baseline level of exit in the largest quintile may be due to merger activity between large producers during this period.

5.1.3 Characteristics of Exiting Firms

The model predicts that firms that shut down in response to increased insurance requirements will have dirtier environmental records due to lower safety effort. Table 4 describes the difference in environmental performance between firms that exited during the bond rollout and those that stayed.

The first column of Table 4 focuses on plugging of inactive wells. I do not observe well-level production, which would allow me to identify non-producing wells. However, I do observe the number and depth of wells owned and their total monthly production. For each firm, I calculate the approximate cost to safely plug all of its wells using the RRC estimate of two dollars per foot of well depth. Firms with a low ratio of revenue to expected plugging costs are more likely to have inactive wells that should have been plugged (once wells are plugged and remediated, they are no longer counted in the firm's number of wells). A low ratio of revenue to plugging costs also makes firms poor credit risks from the point of view of a bond issuer. A firm is less likely to invest in safety effort if the expected future revenue from the business is small.

[35] Of course, using marginal effects to predict the results of non-marginal changes is problematic. Recent work also suggests caution when comparing transitory price shocks with permanent policy changes (Li et al., forthcoming). The goal is not to precisely compare these effects, but rather to emphasize how large the effect of bonding was.

Particularly, it will be more attractive to exit and leave wells unplugged. There is anecdotal evidence that firms with a low ratio of revenue to expected plugging costs received high bond price offers (Texas House of Representatives, 2002). In the first column of Table 4, the dependent variable is an indicator variable equal to one if the firm's expected plugging costs at its most recent license renewal were more than twice its average annual revenue during 1996–2001. The sample contains firms in the industry at the end of 2001. There is one observation per firm. $1[Exit]_i$ is equal to one for firms that exited during 2002. The constant term shows that 9.5% of firms that stayed in the industry after the bonding rule had plugging costs more than twice their average annual revenue. Among exiters, on the other hand, 22.1% of firms had these high plugging costs ($9.5\% + 12.6\% = 22.1\%$).

The final two columns of Table 4 examine the difference in environmental rules violations for exiting vs. staying firms. I compare the number of citations during 1996–2001, normalizing by the number of wells operated during this period. Because of the count nature of the data and the large number of zeros, a count model is most appropriate for estimation. The middle column shows a negative binomial regression of rules violations on $1[Exit]_i$. The estimated coefficient on $1[Exit]_i$ is positive and statistically significant, indicating that exiters were more likely to have had rules violations. The difference between exiters and stayers in the expected count of rules violations per well is given by $e^{\beta} - 1$, where β is the coefficient estimate for $1[Exit]_i$. This calculation shows that exiting firms had 42% more rules violations per well than did firms that stayed in the industry. For robustness, I show an OLS version of the same regression in the final column. The difference in expected violations violations per well is very similar in the OLS and negative binomial specifications.

5.2 Oil and Gas Production

Another prediction of the theoretical model is that judgment-proof firms will reduce their output in response to increased bond requirements. I measure the effect of the bond mandate on firm-level oil and gas production using an event study design that compares firms that have already purchased a bond to firms that have not yet had to purchase a bond. Unlike exit, which is only observed once per year, oil and gas production are observed every month for every firm. This design leverages the panel nature of the data through firm and time fixed effects, which reduce noise and allow me to better measure changes in production.

I run the following regression separately for oil and natural gas production,

$$ln(Production)_{it} = \gamma + \psi 1[Bonded] + \delta_i + \tau_t + \nu_{it} \quad (6)$$

The sample is limited to the 12 months during 2002, and to firms who stayed in the industry after the bond mandate. $1[Bonded]_{it}$ is an indicator variable equal to one for firm-month observations where the license renewal date has already passed. 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. It also 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 I explained in Section 5.1.1, $1[Bonded]_{it}$ is entirely determined by the firm's assigned license renewal date. So, under the assumption that license renewal dates are exogenous with respect to oil and gas production, the regression above consistently estimates the effect of bonding on output.

As a check on this assumption, Appendix Table 1 compares the number and size of firms with license renewal dates in each month. There does not seem to be any pattern in mean output across months. In an F test of the null hypothesis of joint equality across all 12 group means, the F statistic is 0.97 (p-value 0.47).[36] Thus, there does not seem to be any evidence of systematic differences in firms based on the month in which they renew their operating licenses. As an additional robustness check, when I show the results of the production analysis I also show results from a placebo analysis for the year prior to the bond policy change. If differences between renewal month groups introduce bias, it should be apparent in this placebo analysis.

5.2.1 Oil and Gas Production: Graphical Results

Figure 7 visually demonstrates the effect of the bond expansion on firm-level oil production for the smallest 80% of firms. The plotted regression coefficients and 95% confidence intervals correspond to months-from-license-renewal dummy variables. Month 0 is the firm's assigned license renewal month, which varies from January to December 2002; month -1 is the month before, and so on. The sample is limited to firms that remained in the industry after the bond requirement, and further limited to the the smallest 80% of producers, based on firm-level oil and gas output (in barrel of oil equivalents) during 1998–2001. As in Equation 7, firm fixed effects and month-by-revenue-quintile fixed effects are included. The figure shows no apparent trend in production prior to license renewal. Once firms renew their operating licenses, there is a clear decrease in production of about 5%. Individual event month estimates are not statistically different from one another; however, as I show below, I can reject the null hypothesis that production during the post-event months equaled production during the pre-event months for this group of firms.

[36] Because the skewed nature of the data may reduce the power of the F-test, I also perform a nonparametric Kruskal Wallis test. The p-value from this test is 0.86.

5.2.2 Oil and Gas Production: Estimation

Tables 5 and 6 describe the results of equation 7 for firm-level oil and natural gas production, respectively. Table 5 focuses on oil. Column (1) is a regression of logged monthly oil production on $1[Bonded]_{it}$, with firm fixed effects. In this specification, bonding reduces oil production by 4.7% on average across all firms. Column (2) adds month-by-output quintile fixed effects to control for variation over time in other determinants of oil production. This allows for different arbitrary trends for producers in different quintiles. The time fixed effects reduce the estimated effect to 3.2%. In Column (3), I estimate the effect of bonding separately by firm size. Output quintiles for this table are based on average annual production of oil and gas (in barrel of oil equivalents) during 1997–2001. The quintile breaks are given in the left column of the table. The largest effects are for firms in the bottom two quintiles. Bonding reduces oil production among these three groups by 8% and 7%, respectively. In the third and fourth quintiles, bonding has a small and statistically insignificant negative effect. The effect of bonding in the largest quintile is positive, although not statistically significant. A positive effect for large producers may indicate consolidation of the industry as large producers acquire the wells of exiting small firms.

Columns (4) and (5) of Table 5 show a placebo test using data from the previous year (2001) as a check on the identifying assumptions. If oil 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, we would expect to see similar results in previous years as well. There is no statistically significant effect of license renewal on oil production in the placebo analysis.

Table 6 addresses natural gas production. Unlike for oil production, there is no estimated effect of bonding on natural gas production in Columns (1) or (2). In Column (3), there are no statistically significant effects and there does not seem to be any pattern across quintiles in the effect of bonding. As with oil, the placebo analysis in Columns (4) and (5) shows no effect.

One potential explanation for the different results for oil and gas may be that oil is more amenable to "fly-by-night" production models. For example, gas wells must be connected to gathering pipelines in order to deliver product to market, while some oil wells can simply store oil in tanks at the lease to be picked up by truck. Consistent with that story (but not exclusively that story) is the fact that firms that produce at least some gas are larger on average than firms that produce only oil.

5.3 Environmental Outcomes

The theoretical model predicts that increasing bond requirements will decrease environmental incidents. This section examines the effect of increased bond requirements on orphan wells, violations of water protection rules, and well blowouts. I compare outcomes before and after the 2001 policy change. The visual evidence suggests that there were decreases that coincided in time with the increased bond requirement. In the econometric analysis, I run regressions of the form,

$$Y_{it} = \zeta + \phi 1[After]_t + Month_t + u_{it} \tag{7}$$

Y_{it} is an environmental outcome; for example, the monthly count of rules violations at the firm level. $1[After]_t$ is an indicator variable equal to one after the policy change. To allow for anticipatory increases in safety effort by firms trying to lower their expected bond premiums, $1[After]_t$ becomes equal to one in June 2001, when the bill requiring the higher bond amounts passed the Texas Legislature.[37] $Month_t$ is a parametric time trend, and u_{it} is an error term capturing unobserved determinants of the outcome.

Because environmental incidents are rare, several years of outcome data are needed to make empirically meaningful econometric comparisons. Relative to the analysis of producer exit, which examined a small neighborhood around the implementation threshold, and of output, which limited the sample to 2002 and compared already-bonded to not-yet-bonded firms, the analysis of environmental outcomes requires stronger identifying assumptions. It is not possible to definitively rule out other shocks that could have driven some of the observed changes. However, I show that there do not seem to be other regulatory changes that would explain these large changes in environmental outcomes. In addition, for one outcome where similar data are available, I show that outcomes do not change similarly in a neighboring state.

5.3.1 Environmental Outcomes: Graphical Results

Figure 8 shows the share of operators leaving the industry each quarter that left behind orphan wells. Orphan wells are unplugged wells for which no registered operator exists. Firms that exited prior to the end of the twelve-month rollout period would not have been bonded, while firms exiting after the implementation period would have been. There is also little reason to expect anticipatory safety effort in response to the policy change, since orphaning occurs among firms exiting the industry. The vertical line represents December 2002, the end of the rollout period. The data are noisy, but there is an apparent decrease in the share of operators leaving orphan wells at the same

[37] Anticipatory safety effort may also affect firm-level oil and gas production. If so, this would lead me to underestimate the effect of bonding on output in Section 5.2.

time that the increased bonding requirement takes effect. The light gray horizontal lines represent the mean rate of orphaning during five years before and five years after the policy change (in the estimation, I also allow for time trends). The mean rate of orphaning after the policy change is lower by about 50%. Because firms may orphan different numbers of wells, Appendix Figure 3 shows the total number of wells orphaned each quarter before and after policy change. The total number of wells orphaned falls substantially.

Figure 9 shows the total number of water protection rules violations each quarter. These are violations of Statewide Rules 8 and 14, which govern water protection as described in Section 4. The vertical dashed line shows the beginning of the policy implementation period in January, 2002. The lighter dotted line shows the bill's passage in June, 2001. Again, the horizontal gray lines show the mean number of violations during five years before and five years after the policy change. The data are noisy. The number of violations after the policy change is lower, but it is difficult in the figure to separate discrete changes from what may be a smooth downard trend across the implementation threshold.

Figure 10 shows well blowouts. Because blowouts occur most frequently during drilling, in this figure I normalize the number of blowouts by the number of active drilling rigs each quarter.[38] As in the previous figure, the vertical lines represent the policy passage and implementation, and the horizontal lines represent five-year averages before and after the policy change. Before 2001, the time series of blowouts is noisy but relatively flat. There are no clear discrete changes. In 2001, there is a sharp drop in blowouts coincident with the passage of the universal bond mandate. The blowout rate stays low following this change through the end of the panel.

The time series evidence in these figures is suggestive, but it does not rule out other shocks to the oil and gas industry that could have caused these changes. It is not possible to completely overcome this limitation of this portion of the analysis, but it is possible to look for obvious alternative explanations. As one simple robustness check, Figure 11 shows the time series of onshore blowout rates in Louisiana, a nearby state that is also a large oil and gas producer. If blowout rates in Louisiana changed similarly to Texas blowout rates in 2001, that would suggest that the change was related to national-scale shocks to the oil and gas industry, as opposed to Texas regulations. The Louisiana blowout data are from the Louisiana Department of Natural Resources, and, as in the Texas figure, the number of active drilling rigs each month comes from the Baker Hughes Historical Rig Count dataset.[39] The vertical line shows June, 2001, and

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

[39] Louisiana blowout data are from the 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

the horizontal gray lines show five-year mean blowout rates before and after. Perhaps due to lower production, the data prior to 2001 are noisier. There are more quarters with many blowouts, but also more quarters with no blowouts. There may also be a smooth downward trend over time, although the mean blowout rate during the post-period is relatively similar to the pre-period. However, there is not a visually obvious discrete change in the blowout rate in 2001 like there is for Texas.

To consider whether improvements in environmental outcomes may have been caused by other Texas regulatory changes, Appendix Table 3 shows all of the rules that were implemented or amended by the RRC in 2001 and 2002. I include these years to allow for immediate responses to implementation of new regulations, as well as anticipatory responses to regulations announced in 2001 but implemented in later years. 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 driven the observed changes in environmental outcomes. In summary, there do not seem to be obvious confounders that would explain the changes in environmental outcomes that I observe.

5.3.2 Environmental Outcomes: Estimation

Table 7 shows regression estimates of the change in environmental outcomes coincident with the policy change. The first two columns show a linear probability model focused on orphan wells. The sample in these two columns includes one observation per firm, in its month of exit. The dependent variable is an indicator variable equal to one if any of the firm's wells appear on the March 2014 version of the RRC Orphan Well List. $1[After]$ is an indicator variable equal to one in June 2001 and all later months. In Column (1), a simple before/after comparison estimates a 4.4 percentage point decrease in the probability that firms orphan wells upon leaving the industry. This is a 56% decrease from the pre-bonding rate of well orphaning of 7.8%. Column (2) adds a quadratic time trend and month-of-year fixed effects. This reduces the estimated effect slightly to 3.2 percentage points, or a 51% decrease. This effect is consistent with the visual evidence in Figure 8.

Columns (3) and (4) address environmental rules violations. Because of the count nature of the data, I use negative binomial regression.[40] The dependent variable is the count of rules violations each month. This is normalized by the number of wells operated by the firm that month. Column (3) shows that a before/after comparison

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.

[40]For both rules violations and well blowouts, results are similar for poisson and negative binomial models. The negative binomial is preferred because it accommodates overdispersion.

estimates a 14% decrease in the frequency of rules violations per well after the policy change. In Column (4), including an exponential time trend and month-of-year fixed effects increases the estimate slightly, but decreases its statistical significance. Again, the estimated effects are consistent with the graphical evidence in Fig 9.

Columns (5) and (6) address well blowouts. Again, I use negative binomial regression because of the count nature of the data. In these regressions the count of well blowouts in each month is normalized by the number of wells being drilled by the firm in that month. There is a 44% decrease in blowouts in the before/after comparison, and a 67% decrease after controlling for an exponential time trend and month-of-year fixed effects.

The theoretical model predicts that changes in environmental outcomes will result from changes in industry composition (extensive margin changes) and increases in cost internalization by firms that remain in the industry (intensive margin changes). It is interesting to compare the magnitudes of these effects. Table 8 measures the intensive margin effect for rules violations and well blowouts (orphan wells, by definition, apply only to exiting firms). This table repeats the regressions from Columns (3)–(6) of Table 7, limiting the sample to firms that entered the industry before December 2001 and exited after January, 2003 (*i.e.*, firms that stayed in the industry through the bond implementation period).

I focus on the specifications that include time trends and month-of-year fixed effects. For rules violations, Column (2) shows that the intensive margin effect was about a 16% decrease in the average rate of rules violations per well. This is less than the 19% overall decrease when exiting firms are included, which means that exiters had more accidents during the pre-period (This is consistent with the findings in Table 4). But the intensive margin effect is still large. The results for blowouts are similar. Column (4) shows that the intensive margin effect is a 62% decrease, which is smaller than the overall decrease of 67%, but still large.

6 Discussion

The bond requirement reduced the number of small firms and their output, with no effect on larger firms. At the same time, there were substantial improvements in environmental outcomes. These results are consistent with greater cost internalization by judgment-proof firms in response to the bond requirement. Prior to the policy change, financially weak operators could produce oil and gas at a low private cost by exerting minimal safety effort and avoiding any environmental costs through bankruptcy. Bonding made this business model less attractive. Very weak firms had little incentive to exercise safety effort, since it was clearly not in their private interest. Thus, they received high price offers from insurers that effectively pushed them out of the industry. At the same time, operators who became bonded were pressured by insurers to operate safely. Investing in safety reduced the private cost advantage of small firms, so that many sold their assets and left the industry.[41] These changes in the composition of firms and the privately optimal level of safety effort led to decreases in orphan wells, rules violations, and well blowouts.

6.1 Alternative Explanations

6.1.1 Credit Market Inefficiencies

If the surety bond market did not operate efficiently, firms may have received high bond price offers for reasons unrelated to environmental risk. Given the environmental improvements observed, it seems unlikely that bond prices and environmental risk were completely unrelated. Nevertheless, it is worth considering to what degree credit market inefficiencies also contributed to exit. Many insurers and banks offered bonds, so it is unlikely that insurer market power raised bond prices (Gerard and Wilson, 2009). Underwriting expenses do introduce transaction costs, but the qualitative evidence about the effects of the bond policy on exit does not suggest that underwriting costs were a primary driver of producer exit. As discussed, newspaper accounts and legislative records describe a small share of firms receiving very high bond price offers, while typical price offers were only 1-3% of the face value of the bond.

The final potential source of credit market inefficiency is asymmetric information about accident and default risk. Classic models of asymmetric information in credit and insurance markets raise the possibility of excess demand in equilibrium (Jaffee and Russell, 1976; Rothschild and Stiglitz, 1976). The intuition behind these models is that the inability to distinguish high-risk and low-risk types leads the bank or insurer to not offer contracts that would be profitable for the low-risk type, but would be particularly attractive to high-risk types. More recent empirical work has found that supply-side responses to asymmetric information can allow lenders and insurers to serve risky client groups. Adams et al. (2009) and Einav et al. (2013) document how sophisticated credit scoring systems and down payment requirements allow lenders to operate in the market for subprime car loans. Analogous strategies in oil and gas surety bond markets that likely mitigated credit market inefficiencies include credit scoring, availability of detailed information on firms' compliance histories from the RRC, and collateral requirements.

[41] Of the leases belonging to firms that exited in 2002, about 88% were transferred to other operators at the time of exit.

6.1.2 Inefficiently High Bond Requirements

As discussed in Section 3, when bond requirements are large, transaction costs created by collateral requirements can prevent participation by responsible firms. In this case, however, bonds were set far below maximum possible damages. The required bond face values were several thousand dollars per well, or less. While it is difficult to value the damages from a worst-case groundwater or surface water contamination event, they are almost certainly much larger than that.[42] And the costs from a bad well blowout can reach tens of millions of dollars (Jones, 2003). With bond levels so far below maximum possible damages, it is unlikely that capital costs kept out firms that otherwise would have operated safely, because the sum of capital costs and the bond amount was still well below maximum possible damages.

6.2 Welfare

The model in Section 3 provides a framework for evaluating the welfare effects of the expanded bond requirement. The precise welfare impacts depend on several highly uncertain parameters, such as the cost of a groundwater contamination incident. Nevertheless, it is relatively clear that the sign of the welfare effect is positive. Essentially, this policy caused firms to internalize a negative externality to a much greater extent than they had previously. The policy change reduced the frequency of costly environmental damages. It also appears to have re-allocated market share from strategically small judgment-proof producers to more efficient producers, since 88% of the leases belonging to exiting firms were transferred to other producers.

The primary costs created by the policy were increased private costs of safety effort for oil and gas producers. If fines for environmental incidents are set at or below true social damages, profit maximization implies that the net difference of environmental benefits and effort costs is positive. If the marginal cost of safety effort exceeded the expected benefit in terms of reduced environmental costs, firms would not invest further in safety. In practice, expected fines are likely lower than the true social costs because of difficulties in detection, attribution, and enforcement discussed in Section 3.4 and Shavell (2007). There are also transaction costs due to underwriting expenses and collateral requirements. These should be subtracted from the benefits of increased safety to calculate the true net welfare change. However, they are very unlikely to outweigh the environmental benefits. Collateral requirements for firms perceived to be safe producers are small.

[42] Some studies have reported cleanup costs for groundwater contamination incidents, but these values are highly uncertain and highly variable. National Research Council (2013) finds that the average cost to remediate a contaminated groundwater site under the US Resource Conservation and Recovery Act is $11.4 million dollars, and that the average cost to remediate a leaking underground storage tank is $125,000. Greenstone and Gallagher (2008) reports that the average cost to remediate a "Superfund" site is $43 million, but that the average value of cleanups is lower.

In another industry, the sign of the welfare effect might be clouded by competitiveness concerns or by the fact some judgment-proof producers had lower true production costs. In oil and gas, neither of these is likely to be the case. Oil and gas are commodities, and even after the bond policy change, producers in Texas faced essentially perfect competition both within the state and from the world market. There is also no reason to think that exiting firms were more efficient than producers who remained; in fact, as argued previously, they were likely to have been higher-cost firms.

In fact, there is an argument to be made that bond requirements in Texas are still below the optimal level. Calculating the optimal bond amount requires estimates of the value of accident damages, h, the effort elasticity of environmental damages, $\gamma'(x)$, and the capital costs imposed on firms by tying up collateral, r. These are mostly unknown. However, the empirical analysis showed that the elasticity of environmental damages over the observed change in bond requirements was large. If further modest increases in bonds were to yield similar improvements, the value of environmental improvements would almost certainly be larger than the costs.

7 Conclusion

This paper focuses on a historical case study, but the results are even more relevant today. Between 2006 and 2013, U.S. oil production increased by 65% and natural gas production by 40%, largely due to hydraulic fracturing. In 2015, annual crude oil production is expected to be at its highest level since 1970.[43] The oil and gas boom has had economy-wide benefits. At the same time, it presents environmental challenges on a massive scale. The large number of projects being developed creates more risk of accidents, and the deployment of new chemicals and techniques creates novel risks.

The oil and gas industry nationwide still includes many small firms. Davis (forthcoming) demonstrates the lack of concentration in onshore natural gas drilling. A back-of-the-envelope calculation suggests that the majority of firms drilling new gas wells in 2012 had annual revenues of several million dollars or less. This means that their effective liability exposure is much less than the damages from a major groundwater contamination incident, well blowout, or spill into surface water.

At the same time, bond requirements in most jurisdictions remain at very low levels. The minimum bond requirements for oil and gas production on federal lands have not been increased since 1960, even to adjust for inflation. The Texas requirements

[43]Oil and gas production growth are calculated from U.S. Energy Information Administation (EIA) "U.S. Field Production of Crude Oil" and "U.S. Natural Gas Gross Withdrawals" data. The 2015 forecast of 9.5 million barrels per day is from the EIA Short-Term Energy Outlook, October 2014.

examined in this paper are some of the highest in the country (Appendix Figure 4), and they are still small compared to maximum potential damages. The positive effects of bond requirements observed in this study create an argument to increase bonds in other jurisdictions at least to the levels observed in Texas. While it is impossible to extrapolate beyond the observed bond levels, it also seems likely that somewhat higher bond requirements would yield further benefits because of the large gap between current bond levels and potential damages.

More broadly, this paper extends our understanding of bankruptcy and market structure in dangerous industries. The theoretical model formalizes the economics of this relationship. The empirical analysis provides highly credible quasi-experimental evidence that validates the theoretical predictions. As expected, the judgment-proof problem inflated the number of small producers, and led them to produce more than was efficient while exerting less-than-efficient safety effort.

These results suggest that bankruptcy should be taken seriously as a determinant of market structure in industries with substantial liability exposure. Within the energy sector, this has implications for transportation of oil, natural gas, and gasoline and other refined products by pipeline, road, and rail.[44] Other examples of sectors with small firms and high liability risk include chemical manufacturing, transportation network companies, and retail gasoline. More work in other settings will help to gauge the generality of these results, but the findings of this study demonstrate the important 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.

References

Adams, William, Liran Einav, and Jonathan Levin, "Liquidity Constraints and Imperfect Information in Subprime Lending," *American Economic Review*, 2009, *99* (1), 49–84.

Alberini, Anna and David Austin, "Accidents Waiting to Happen: Liability Policy and Toxic Pollution Releases," *The Review of Economics and Statistics*, November 2002, *84* (4), 729–741.

Allcott, Hunt and Daniel Keniston, "Dutch Disease or Agglomeration? The Local Economic Effects of Natural Resource Booms in Modern America," Working Paper 20508, National Bureau of Economic Research. September 2014.

[44]In July 2013, a train carrying crude oil derailed and exploded in Lac-Mégantic, Quebec, killing 47 people. The total damages were estimated at $200 million. The railroad, which had a $25 million liability insurance policy, declared bankruptcy. Morris, Betsy. "Fiery Oil-Train Accidents Raise Railroad Insurance Worries." *Wall Street Journal*. January 8, 2014.

Alquist, Ron and Lutz Kilian, "What do we learn from the price of crude oil futures?," *Journal of Applied Econometrics*, 2010, *25* (4), 539–573.

Anderson, Owen L, "The Anatomy of an Oil and Gas Drilling Contract," *Tulsa LawJournal*, 1989, *25*, 359.

Bain, Joe S., *Barriers to new competition: their character and consequences in manufacturing industries*, Harvard University Press Cambridge, MA, 1956.

Banerjee, Abhijit V and Esther Duflo, "Growth theory through the lens of development economics," *Handbook of economic growth*, 2005, *1*, 473–552.

Bloom, Nicholas, Raffaella Sadun, and John Van Reenen, "The Organization of Firms Across Countries," *The Quarterly Journal of Economics*, 2012, *127* (4), 1663–1705.

Boyd, James, "Financial responsibility for environmental obligations: An analysis of environmental bonding and assurance rules," *T. Swanson, Law and Economics of Environmental Policy, Research in Law and Economics Series, Elsevier*, 2002.

_ **and Daniel E Ingberman**, "Fly by night or face the music? Premature dissolution and the desirability of extended liability," *American Law and Economics Review*, 2003, *5* (1), 189–232.

Brooks, Richard RW, "Liability and Organizational Choice," *Journal of Law and Economics*, 2002, *45* (1), 91–125.

Che, Yeon-Koo and Kathryn E. Spier, "Strategic judgment proofing," *The RAND Journal of Economics*, 2008, *39* (4), 926–948.

Darrah, Thomas H., Avner Vengosh, Robert B. Jackson, Nathaniel R. Warner, and Robert J. Poreda, "Noble gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales," *Proceedings of the National Academy of Sciences*, 2014, *111* (39), 14076–14081.

Davis, Lucas, "Bonding Requirements for Natural Gas Producers," *Review of Environmental Economics and Policy*, forthcoming.

Einav, Liran, Mark Jenkins, and Jonathan Levin, "The impact of credit scoring on consumer lending," *The RAND Journal of Economics*, 2013, *44* (2), 249–274.

Ganuza, Juan José and Fernando Gomez, "Soft Negligence Standards and the Strategic Choice of Firm Size," *The Journal of Legal Studies*, 2011, *40* (2), 439–466.

Gerard, David, "The law and economics of reclamation bonds," *Resources Policy*, 2000, *26* (4), 189–197.

_ **and Elizabeth J Wilson**, "Environmental bonds and the challenge of long-term carbon sequestration," *Journal of Environmental Management*, 2009, *90* (2), 1097–1105.

Greenstone, Michael and Justin Gallagher, "Does Hazardous Waste Matter? Evidence from the Housing Market and the Superfund Program," *The Quarterly Journal of Economics*, 2008, *123* (3).

Harkins, Robert M, "Lender Liability under Superfund: New Rules-Old Rules-No Rules," *Environs: Environmental Law & Policy Journal*, 1994, *17*, 18.

Hsieh, Chang-Tai and Benjamin A. Olken, "The Missing 'Missing Middle'," *Journal of Economic Perspectives*, Summer 2014, *28* (3), 89–108.

Jaffee, Dwight M. and Thomas Russell, "Imperfect Information, Uncertainty, and Credit Rationing," *The Quarterly Journal of Economics*, 1976, *90* (4), pp. 651–666.

Jones, Stephanie K., "Working With Blowouts, Knock-for-Knocks and Other Oil Patch Oddities," *Insurance Journal*, June 9, 2003.

Kaiser, Mark J. and Brian Snyder, "Raising supplemental bonding ups small company liabilities," *Oil and Gas Journal*, September 7, 2009.

Kell, Scott, "State Oil and Gas Agency Groundwater Investigations And Their Role in Advancing Regulatory Reforms-A Two-State Review: Ohio and Texas," Technical Report 2011.

Kellogg, Ryan, "Learning by drilling: Interfirm learning and relationship persistence in the Texas oilpatch," *The Quarterly Journal of Economics*, 2011, p. 39.

Kornhauser, Lewis A, "An economic analysis of the choice between enterprise and personal liability for accidents," *California Law Review*, 1982, pp. 1345–1392.

Li, Shanjun, Joshua Linn, and Erich Muehlegger, "Gasoline Taxes and Consumer Behavior," *American Economic Journal: Economic Policy*, forthcoming.

LoPucki, Lynn M, "The death of liability," *Yale Law Journal*, 1996, pp. 1–92.

Lucas, Robert E, "On the size distribution of business firms," *The Bell Journal of Economics*, 1978, pp. 508–523.

Muehlenbachs, Lucija, Elisheba Spiller, and Christopher Timmins, "The Housing Market Impacts of Shale Gas Development," Working Paper 19796, National Bureau of Economic Research. January 2014.

Murray, Milissa A and Sandra Franco, "Treatment of Environmental Liabilities in Bankruptcy," in James B Witkin, ed., *Environmental Aspects of Real Estate and Commercial Transactions*, American Bar Association, 2011.

National Research Council, "Alternatives for Managing the Nation's Complex Contaminated Groundwater Sites," Technical Report, Committee on Future Options for Management in the Nation's Subsurface Remediation Effort 2013.

Pitchford, Rohan, "How liable should a lender be? The case of judgment-proof firms and environmental risk," *The American Economic Review*, 1995, pp. 1171–1186.

Polborn, Mattias K, "Mandatory insurance and the judgment-proof problem," *International Review of Law and Economics*, 1998, *18* (2), 141–146.

Rauch, James E., "Modelling the informal sector formally," *Journal of Development Economics*, 1991, *35* (1), 33 – 47.

Ringleb, Al H and Steven N Wiggins, "Liability and large-scale, long-term hazards," *Journal of Political Economy*, 1990, pp. 574–595.

Rothschild, Michael and Joseph Stiglitz, "Equilibrium in Competitive Insurance Markets: An Essay on the Economics of Imperfect Information," *The Quarterly Journal of Economics*, 1976, *90* (4), 629–649.

Shavell, Steven, "A model of the optimal use of liability and safety regulation," *The Rand Journal of Economics*, 1984, *15* (2), 271–280.

_ , "The Judgment Proof Problem," *International Review of Law and Economics*, 1986, *6* (1), 45–58.

_ , "Minimum asset requirements," Working Paper 9335, National Bureau of Economic Research. 2002.

_ , "Minimum Asset Requirements and Compulsory Liability Insurance as Solutions to the Judgment-Proof Problem," *RAND Journal of Economics*, 2005, pp. 63–77.

_ , "Chapter 2 Liability for Accidents," in A.M. Polinsky and S. Shavell, eds., , Vol. 1 of *Handbook of Law and Economics*, Elsevier, 2007, pp. 139 – 182.

STRONGER, *State Review of Oil and Natural Gas Environmental Regulations: Texas State Review*, Environmental Protection Agency and Interstate Oil and Gas Compact Commission, 2003.

Texas House of Representatives, "House Committee on Environmental Regulation Interim Report 2002," November 23 2002.

Viner, Jacob, *Cost curves and supply curves*, Springer, 1932.

White, Michelle J., "Chapter 14: Bankruptcy Law," in A.M. Polinsky and S. Shavell, eds., , Vol. 2 of *Handbook of Law and Economics*, Elsevier, 2007, pp. 1013 – 1072.

Yin, Haitao, Alex Pfaff, and Howard Kunreuther, "Can Environmental Insurance Succeed Where Other Strategies Fail? The Case of Underground Storage Tanks," *Risk Analysis*, 2011, *31* (1), 12–24.

Figure 1: Long-Run Average Cost Functions In a Hazardous Industry

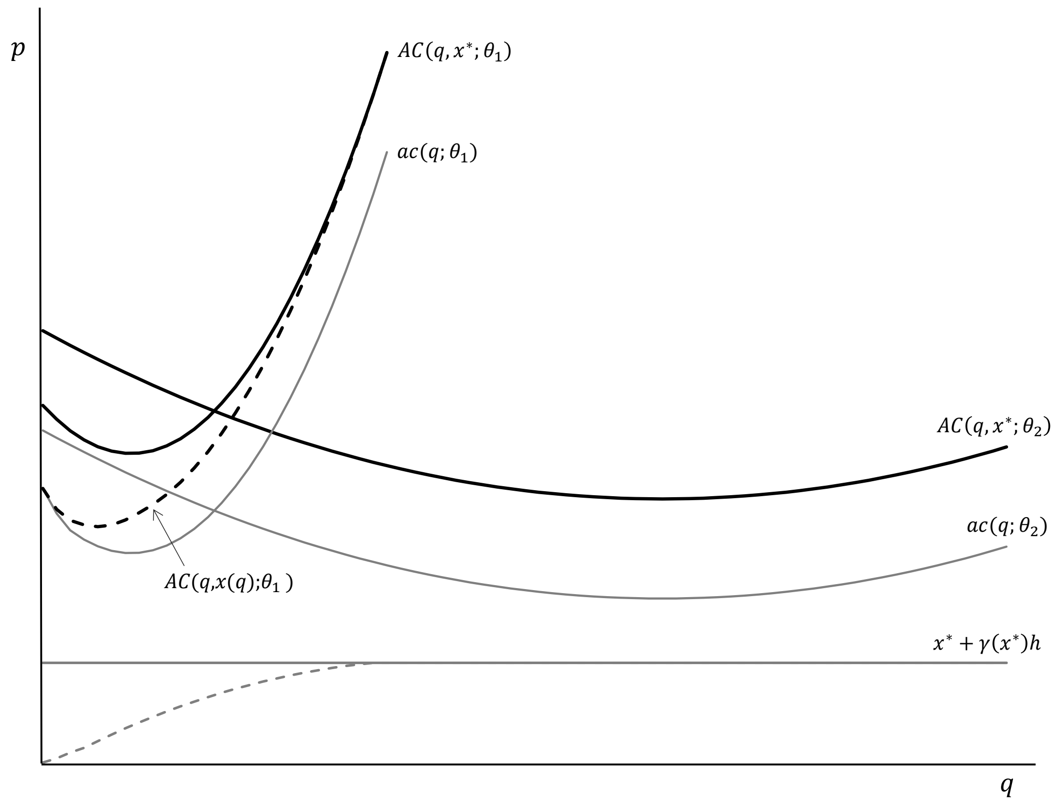
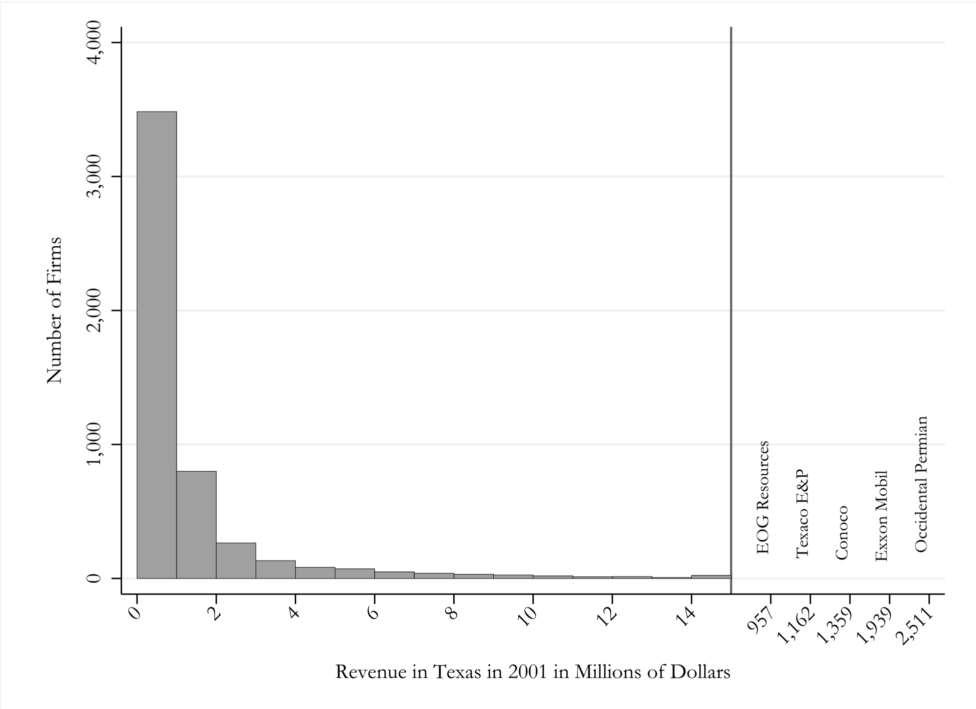
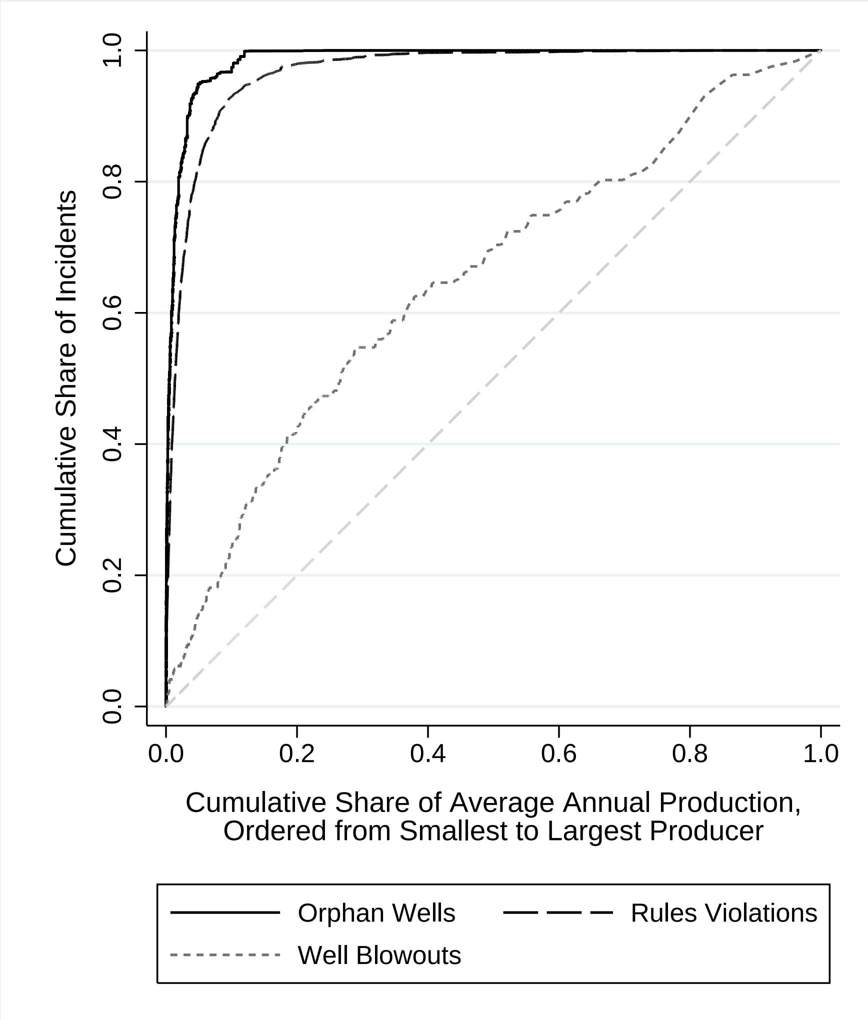


Figure 2: Size Distribution of Oil and Gas Producers in Texas



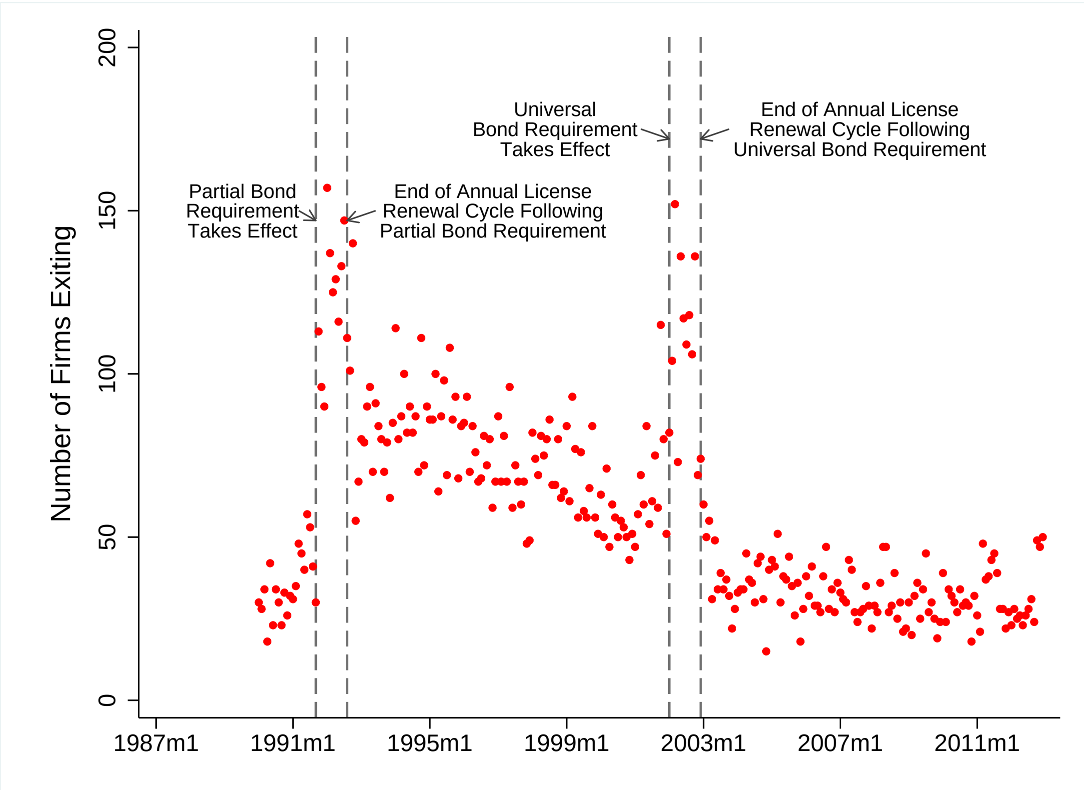
Notes: This figure shows the distribution of year 2001 production revenues for the 5,302 oil and gas producers that were in the industry for the full year. Revenues are calculated using EIA Texas first purchase prices for oil and EIA Texas wellhead prices for natural gas. Dollar amounts are in 2010 dollars. The x-axis is truncated between 15 million and 957 million dollars; 239 firms with revenues in this range are not shown.

Figure 3: Cross-sectional Comparison of Environmental Incidents and Firm Size



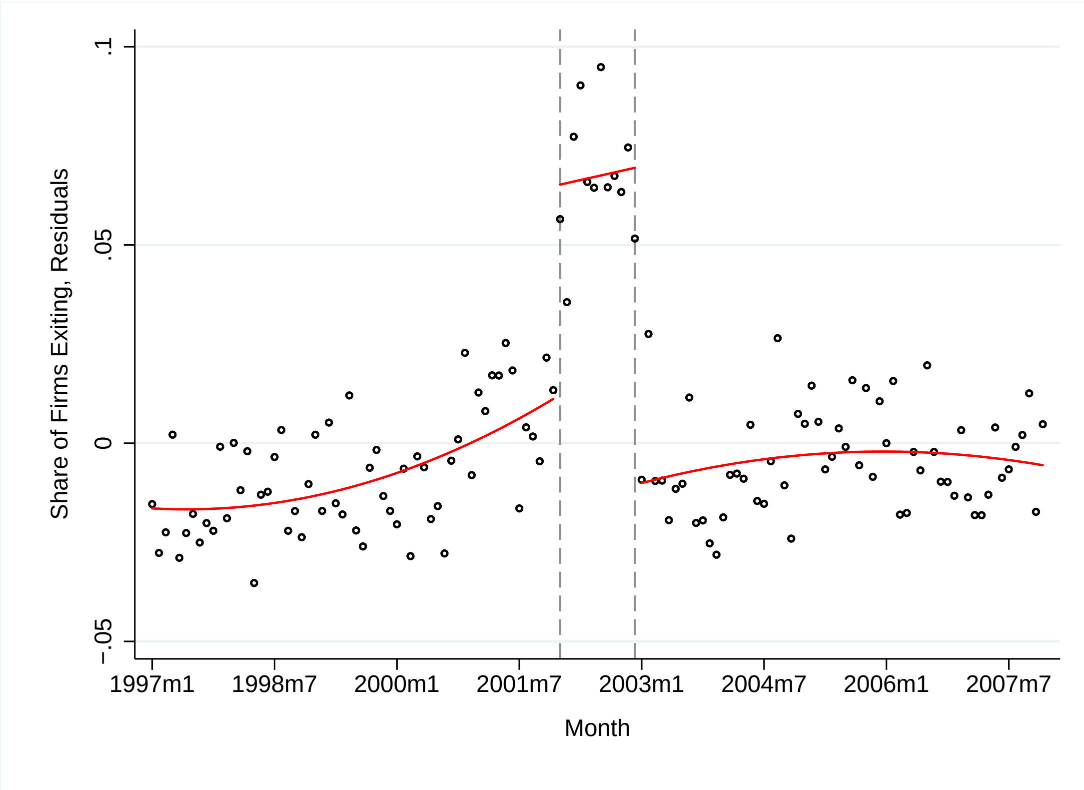
Notes: This figure shows that environmental incidents are concentrated among the smallest firms. The figure uses data from 1990 to 2001. For each firm, I calculate average annual oil and gas production in barrel of oil equivalents (1 BOE = 1 barrel of oil or 6 thousand cubic feet of natural gas). The x-axis represents the sum of average annual production for all firms. Producers are ordered from left to right on this axis, so that, for example, 0.2 represents the 20% of total annual production that comes from the smallest firms. The y-axis represents the total number of environmental incidents during this period. So, 0.4 on the y-axis corresponds to 40% of total incidents during 1990–2001. The gray dashed line has a slope of 1; if incidents were equally common at all firm sizes, the data would follow this line.

Figure 4: Number of Firms Exiting by Month



Notes: This figure shows the number of firms leaving the industry each month. Exit date is defined as 365 days after the firm's final annual operating license renewal. The sample includes all firms with oil or gas leases from 1990 to 2010. The initial rollout of the partial bond requirement occurred during September, 1991 to August, 1992. The initial rollout of the universal bond requirement occurred during January–December, 2002.

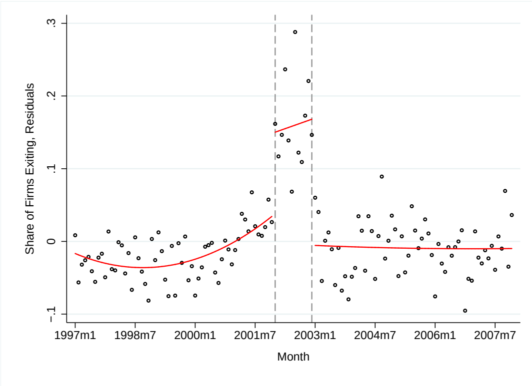
Figure 5: The Effect of the 2001 Bond Requirement on Exit



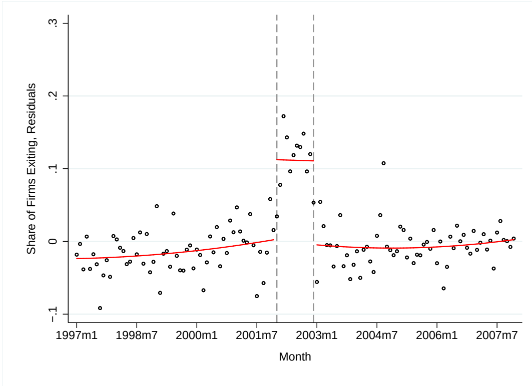
Notes: This figure shows the effect of the 2001 bond requirement on exit. The sample includes all firms that produced oil or natural gas during 1997–2006, and that reported at least six months of production during 1996–2007. There is one observation per firm per year, in the firm's assigned license renewal month. The dots are monthly means of the residuals from a regression of an indicator variable for exit on month-of-year fixed effects and monthly crude oil prices. The red curves represent a quadratic polynomial fit for 1997–2001, a separate linear polynomial for 2002, and a separate quadratic polynomial fit for 2003-2006. Month 0 is January 2002.

Figure 6: The Effect of the 2001 Bond Requirment on Exit, by Firm Size

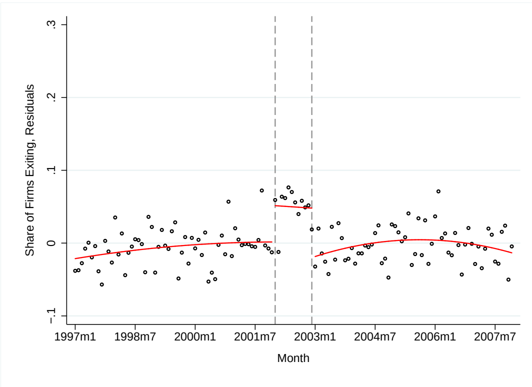
(a) 1st Quintile



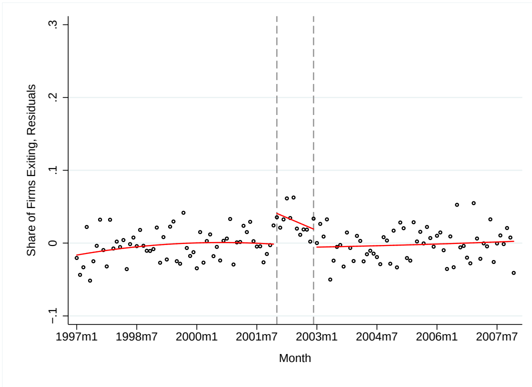
(b) 2nd Quintile



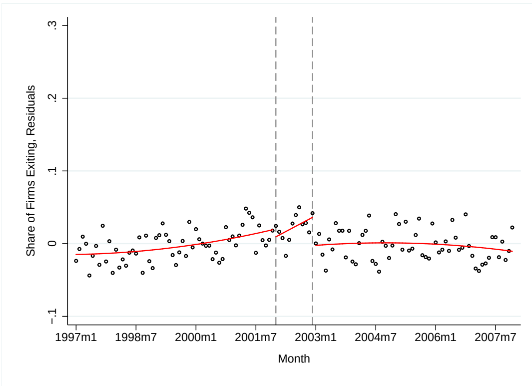
(c) 3rd Quintile



(d) 4th Quintile

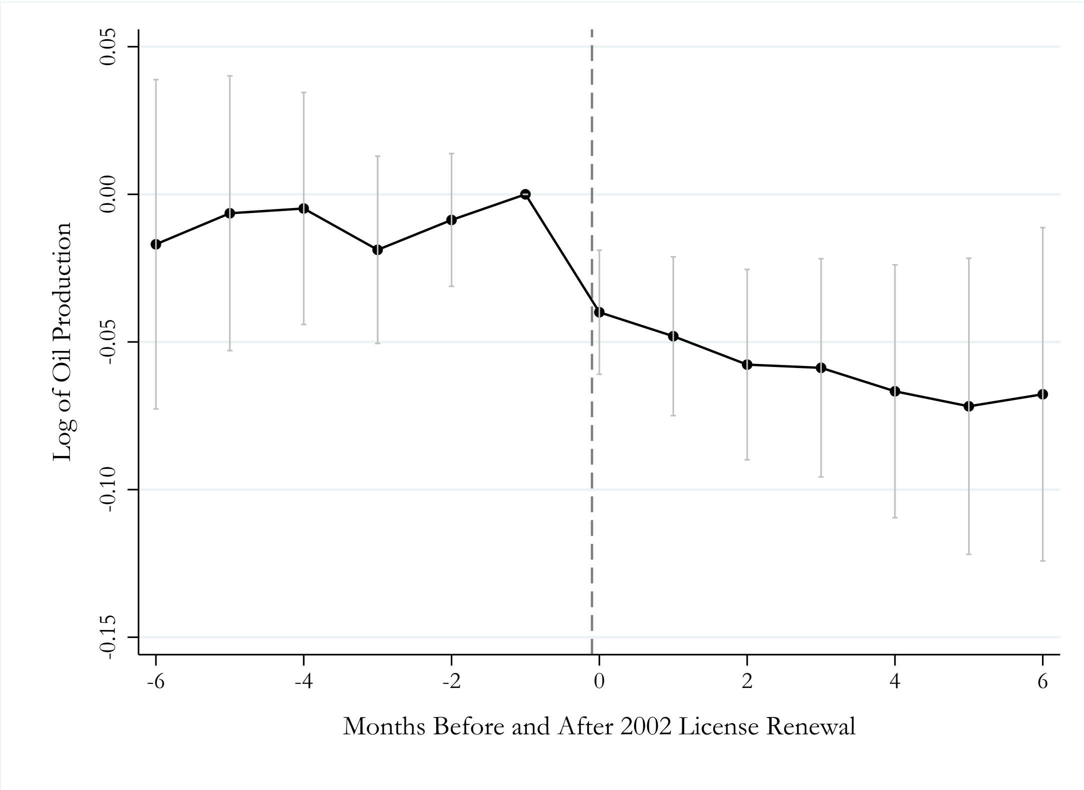


(e) 5th Quintile



Notes: This figure shows the effect of the bond requirement on exit by quintile of firm size. The sample and analysis are the same as in Figure 5. Each panel shows results from a single quintile of the output distribution. Output is calculated as average annual production for 1997 to 2006 in barrels of oil equivalent (BOE). One BOE equals one barrel of crude oil or six MCF of natural gas. Average annual production is 12 times the average monthly production across all non-zero months.

Figure 7: Oil Production By Small Firms Before and After Bonding



Notes: This figure shows the effect of bonding on monthly oil production for the smallest 80% of firms. The horizontal axis shows time relative to the firm's assigned license renewal month (which ranges from January to December 2002). The sample is limited to firms that remained in the industry after the bond requirement, and to the bottom four quintiles of the output distribution. See text for details. The plotted points represent regression coefficients on indicator variables equal to one when the firm is a corresponding number of months away from license renewal. Vertical bars represent 95% confidence intervals. The omitted category is t=-1, the month before renewal. These regressions include firm and month-of-sample-by-revenue-quintile fixed effects. Revenue quintiles are defined as in Table 5. Standard errors are clustered at the firm level.

Figure 8: Share of Exiters Orphaning Wells, by Quarter of Exit

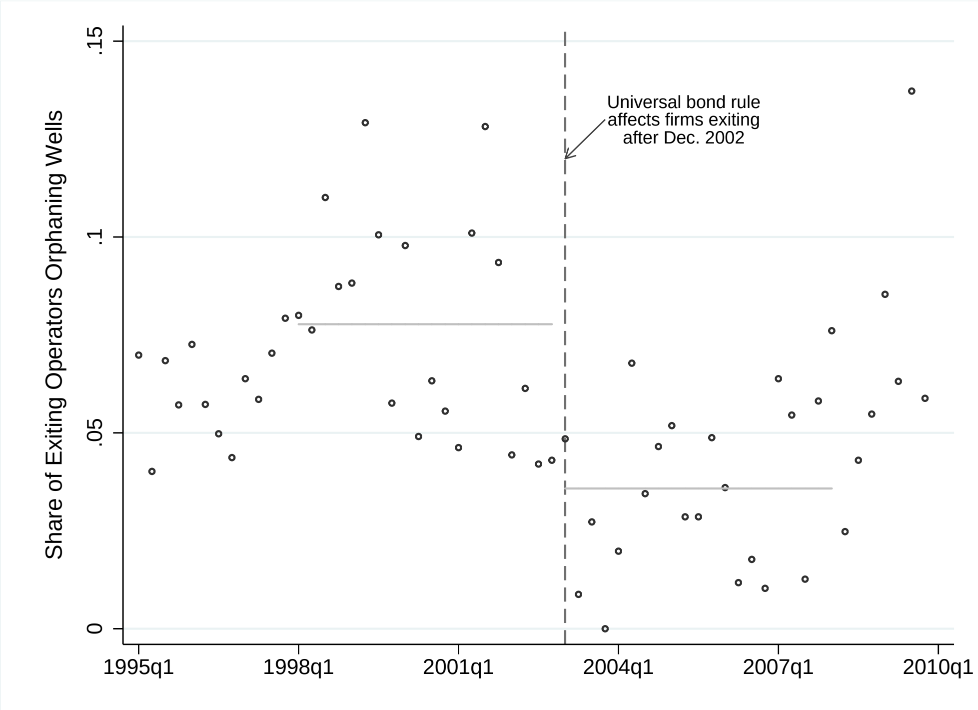


Figure 9: Water Protection Rules Violations by Quarter

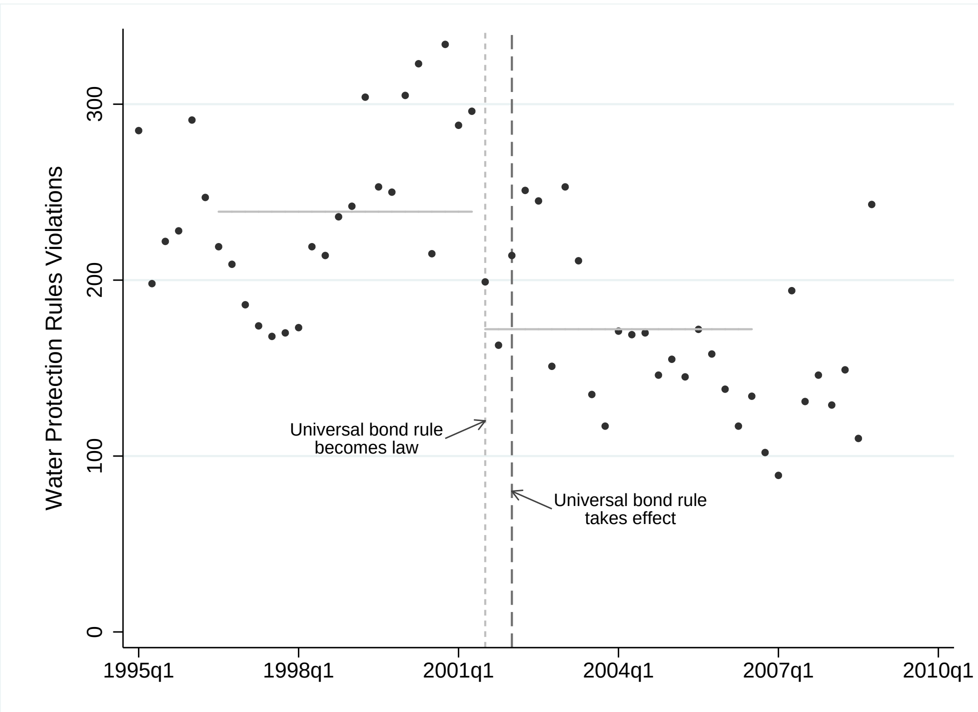


Figure 10: Well Blowouts by Quarter

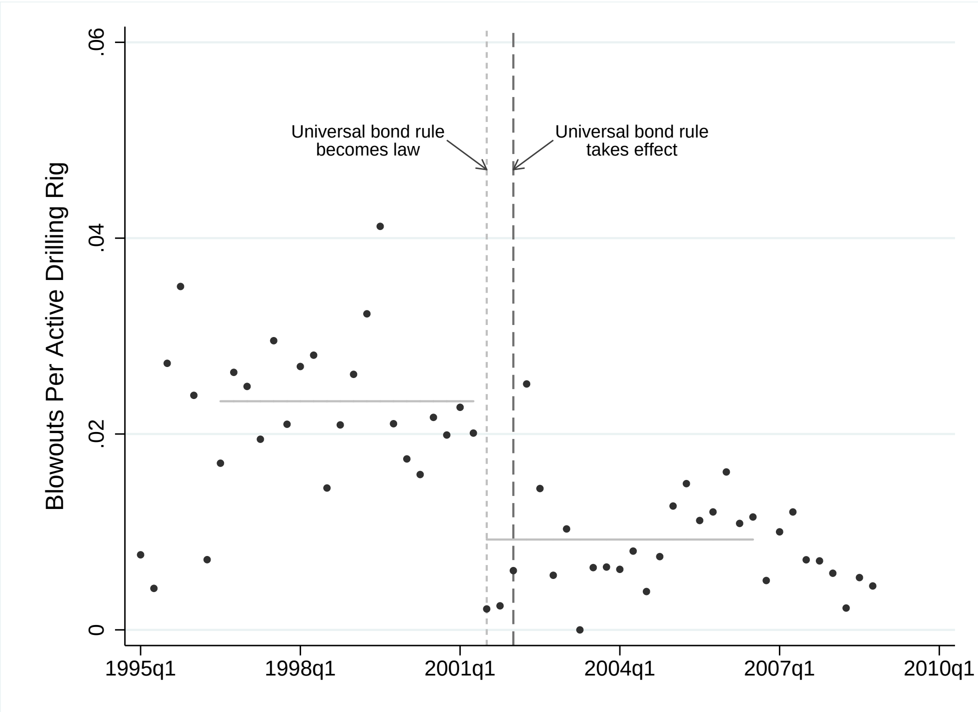


Figure 11: Well Blowouts in Louisiana by Quarter

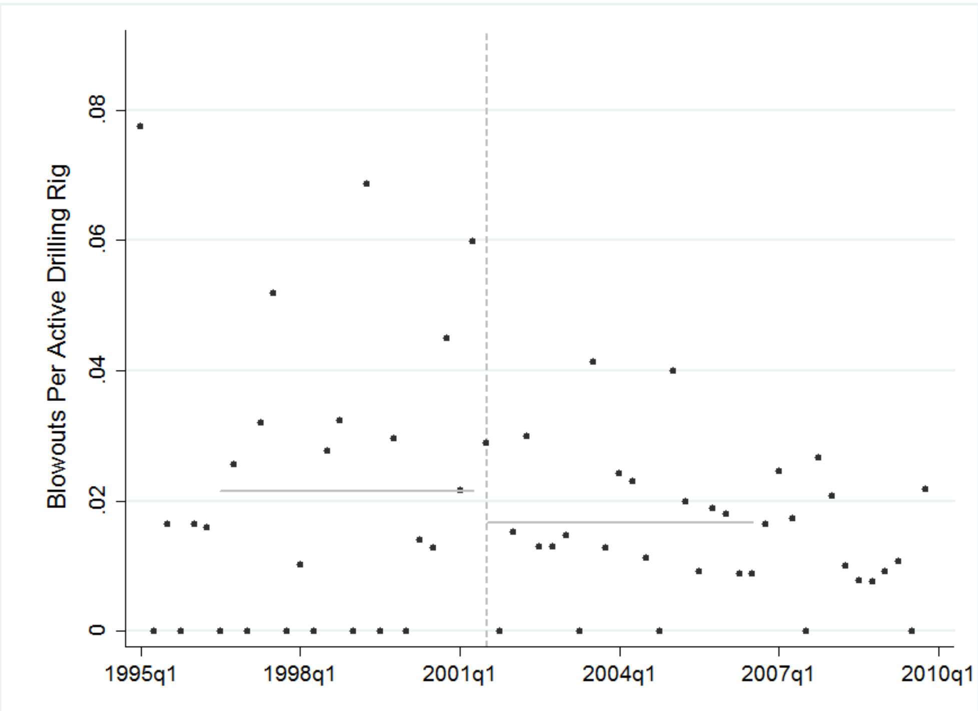


Table 1: Quintiles of Annual Production Revenue Per Firm in 2001

5	$2,510,918,000
4	$1,391,000
3	$344,000
2	$114,000
1	$33,0000

Notes: This table lists quintiles of year 2001 production revenue for the 5,302 oil and gas producers that were in the industry for the full year. 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.

Table 2: Effect of the Bond Requirement on Exit

	(1)	(2)	(3)
Begin Rollout	0.068***	0.063***	0.060***
	(0.010)	(0.010)	(0.010)
End Rollout	−0.082***	−0.084***	−0.083***
	(0.011)	(0.013)	(0.013)
Oil Price		−0.044**	−0.051**
($100/bbl)		(0.020)	(0.021)
Constant	0.090***	0.089***	0.093***
	(0.006)	(0.005)	(0.006)
Month-of-year FE	No	No	Yes
Local Time Polynomial	Yes	Yes	Yes
N	71,826	71,826	71,826
Firms	10,978	10,978	10,978

Notes: This table reports the results of 3 separate OLS regressions. The sample includes 1997 – 2007 and includes all firms with at least six months of oil or natural gas production during 1996–2007. 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 for exit in a given year. Begin Rollout is an indicator variable equal to one starting in January 2002. End Rollout is an indicator variable equal to one starting in January 2003. All specifications include a quadratic polynomial in time for 1997–2001; a separate linear polynomial for 2002; and a separate quadratic polynomial for 2003–2007. 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 3: 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	0.121***	0.120***	0.056***	0.045***	−0.011
	(0.014)	(0.025)	(0.017)	(0.013)	(0.013)
End Rollout	−0.158***	−0.114***	−0.095***	−0.049**	−0.014
	(0.029)	(0.022)	(0.018)	(0.019)	(0.015)
Oil Price	−0.115**	−0.083**	−0.081**	−0.030	0.025
($100/bbl)	(0.048)	(0.033)	(0.033)	(0.023)	(0.033)
Constant	0.170***	0.094***	0.079***	0.050***	0.097***
	(0.013)	(0.020)	(0.012)	(0.008)	(0.010)
N	11,903	13,267	14,667	16,197	15,792
Firms	2,129	2,185	2,202	2,226	2,236

Notes: This table reports estimates separately by output quintile for the regression specification shown in Column 3 of Table 2. Each column shows results from a regression that includes one quintile of the output distribution. Output is calculated as average annual production during 1996–2007 in barrels of oil equivalent (BOE). One BOE equals one barrel of crude oil or six MCF of natural gas. Average annual production is 12 times the average monthly production across all non-zero months. All regressions include month-of-year fixed effects and the same local polynomial in time as in Table 2. Standard errors are clustered by quarter. *** indicates statistical significance at the 1% level; ** at the 5% level; * at the 10% level

Table 4: The Relative Environmental Performance of Exiting Firms

	Plugging Costs > 2 Years Revenue	Water Protection Rules Violations	
	OLS	Neg. Binomial	OLS
$1[Exit]$	0.126***	0.348**	6.999
	(0.015)	(0.143)	(4.319)
% Difference in Expected Count	133%	42%	38%
Constant	0.095***	2.775***	18.329***
	(0.005)	(0.067)	(1.415)
Normalization	None	Thousand Wells	Thousand Wells
Firms	4,868	4,868	4,868

Notes: This table reports the results of three separate regressions. The sample includes firms active at the end of 2001 with at least 6 months of production during 1996–2001. There is one observation per firm. $1[Exit]$ is an indicator variable equal to one for firms that exited during the bond rollout in 2002. In the first column, the dependent variable is an indicator variable equal to one if the estimated cost to plug all of the firm's wells at its most recent license renewal was more than twice the firms's average annual production revenue during 1996–2001. In the second and third columns, the dependent variable is the count of violations of Statewide Rules 8 or 14 during June 1996 – June 2001. This is normalized by the average number of wells operated during the same period (in thousands of wells, for readability). For OLS, the normalization is implemented by dividing by the number of wells; for the negative binomial, the log of wells is included as a regressor with coefficient constrained to one. For OLS specifications, the % difference between groups is the regression coefficient β divided by the mean outcome for the non-exiting firms. For the negative binomial, the % difference is $exp(\beta) - 1$. See text for details. Standard errors are Eicker-White heteroscedasticity-consistent. *** indicates statistical significance at the 1% level; ** at the 5% level; and * at the 10% level.

Table 5: Effect of Bonding on Oil Production for Remaining Firms

	Implementation Year			Placebo Year	
	(1)	(2)	(3)	(4)	(5)
1[Bonded]	−0.047***	−0.032***		0.001	
	(0.009)	(0.010)		(0.011)	
1[Bonded]*Quintile 1 (1,800 BOE)			−0.079***		0.006
			(0.030)		(0.034)
1[Bonded]*Quintile 2 (5,700 BOE)			−0.074***		−0.024
			(0.025)		(0.023)
1[Bonded]*Quintile 3 (16,100 BOE)			−0.011		0.028
			(0.022)		(0.022)
1[Bonded]*Quintile 4 (60,200 BOE)			−0.027		−0.009
			(0.020)		(0.018)
1[Bonded]*Quintile 5 (60,000,000 BOE)			0.014		0.005
			(0.021)		(0.022)
Constant	6.071***	6.059***	6.052***	6.037***	6.054***
	(0.005)	(0.013)	(0.013)	(0.009)	(0.012)
Firm Fixed Effects	Yes	Yes	Yes	Yes	Yes
Mon-by-Quint FE	No	Yes	Yes	Yes	Yes
N	48,600	48,600	48,600	49,990	49,990
Firms	4,571	4,571	4,571	4,583	4,583

Notes: This table reports the results of 5 unweighted OLS regressions. The dependent variable is the log of monthly oil production in barrels at the firm level. In Columns (1) – (3), the sample is limited to 2002, and to firms who renewed their annual operating license in that year (*i.e.*, who became bonded) and had positive oil production during 1997 – 2001. In Columns (4) and (5), the sample is limited to 2001, and to firms who renewed their annual operating license in that year. 1[*Bonded*] is an indicator variable equal to one in all months after a firm's license renewal month, and equal to zero in all earlier months. Output quintiles are based on average annual production of oil and gas (in barrel-of-oil equivalents) during 1997 – 2001. See text for details. Standard errors are clustered at the operator level. *** indicates statistical significance at the 1% level; ** at the 5% level; * at the 1% level.

Table 6: Effect of Bonding on Natural Gas Production for Remaining Firms

	Implementation Year			Placebo Year	
	(1)	(2)	(3)	(4)	(5)
1[Bonded]	−0.017	−0.007		−0.001	
	(0.012)	(0.012)		(0.014)	
1[Bonded]*Quintile 1			−0.027		−0.022
(1,800 BOE)			(0.035)		(0.040)
1[Bonded]*Quintile 2			0.042		−0.007
(5,700 BOE)			(0.032)		0.036)
1[Bonded]*Quintile 3			−0.028		0.039
(16,100 BOE)			(0.027)		(0.036)
1[Bonded]*Quintile 4			−0.034		−0.017
(60,200 BOE)			(0.028)		(0.023)
1[Bonded]*Quintile 5			0.011		−0.003
(60,000,000 BOE)			(0.017)		(0.024)
Constant	7.374***	7.343***	7.341***	7.311***	7.309***
	(0.007)	(0.015)	(0.015)	(0.015)	(0.016)
Firm Fixed Effects	Yes	Yes	Yes	Yes	Yes
Mon-by-Quint FE	No	Yes	Yes	Yes	Yes
N	41,493	41,493	41,493	43,180	43,180
Firms	4,067	4,067	4,067	4,082	4,082

Notes: This table reports the results of 5 unweighted OLS regressions. The dependent variable is the log of monthly natural gas production in MCF at the firm level. In Columns (1) – (3), the sample is limited to 2002, and to firms who renewed their annual operating license in that year (*i.e.*, who became bonded) and had positive gas production during 1998 – 2001. In Columns (4) and (5), the sample is limited to 2001, and to firms who renewed their annual operating license in that year. 1[*Bonded*] is an indicator variable equal to one in all months after a firm's license renewal month, and equal to zero in all earlier months. Output quintiles are based on average annual production of oil and gas (in barrel-of-oil equivalents) during 1997 – 2001. See text for details. Standard errors are clustered at the operator level. *** indicates statistical significance at the 1% level; ** at the 5% level; * at the 1% level.

Table 7: The Effect of Increased Bond Requirements on Environmental Incidents

	Orphan Wells (OLS)		Water Protection Rules Violations (Negative Binomial)		Well Blowouts (Negative Binomial)	
	(1)	(2)	(3)	(4)	(5)	(6)
$1[After]$	-0.044^{***}	-0.032^{**}	-0.148^{**}	-0.212	-0.576^{***}	-1.107^{***}
	(0.007)	(0.015)	(0.067)	(0.142)	(0.159)	(0.299)
% Change in Expected Count	**-56%**	**-51%**	**-14%**	**-19%**	**-44%**	**-67%**
Constant	0.078^{***}	0.063^{***}	-8.054^{***}	-8.087^{***}	-6.666^{***}	-6.164^{***}
	(0.005)	(0.016)	(0.048)	(0.103)	(0.080)	(0.196)
Time Trend	None	Quadratic	None	Exponential	None	Exponential
Month-of-Year FE	No	Yes	No	Yes	No	Yes
Normalization	None	None	Wells Operated	Wells Operated	Wells Drilled	Wells Drilled
N	5,307	5,307	593,891	593,891	56,771	56,771
Firms	5,307	5,307	9,809	9,809	5,043	5,043

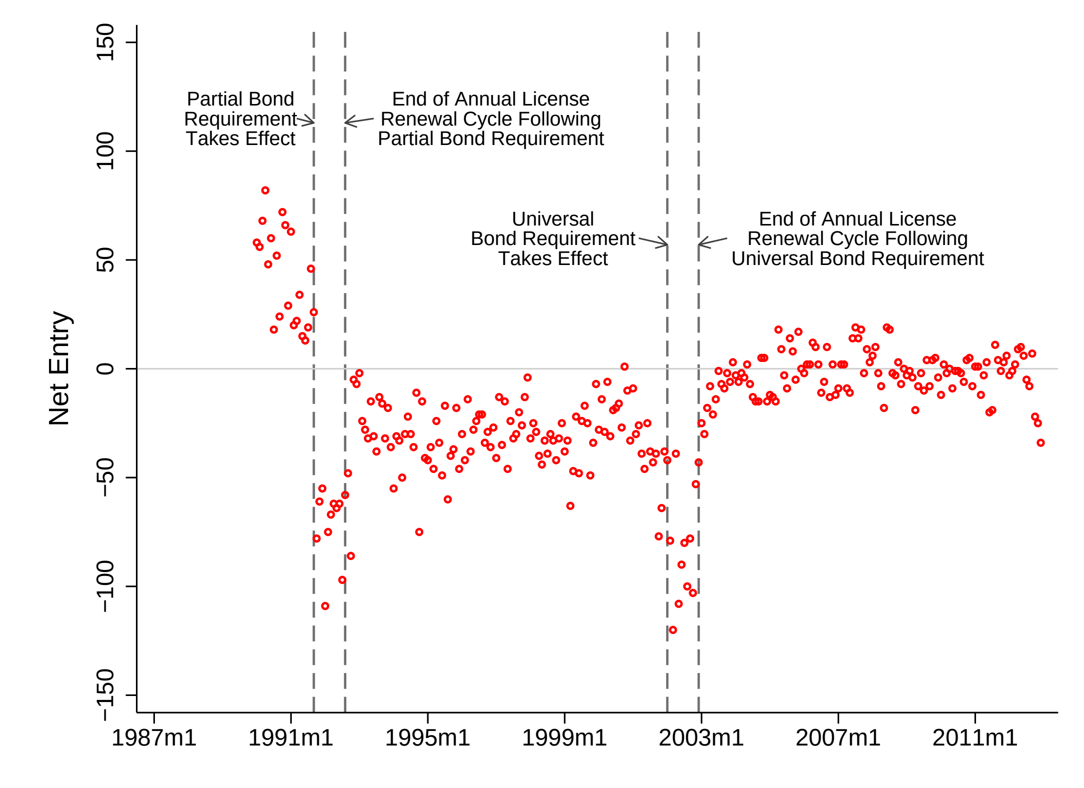
Notes: This table reports the results of six separate regressions. In each case, the sample period covers June 1996 to June 2006. Columns (1) and (2) show OLS regressions where the dependent variable is an indicator variable equal to one if the firm orphaned any wells that appear on the March 2014 version of the RRC Orphan Well list. All firms that exited during the sample period are included. There is one observation per firm in its month of exit. Columns (3) and (4) show negative binomial regressions where the dependent variable is the monthly count of violations of Statewide Rules 8 or 14. The sample includes all firm-months with positive oil or gas production. Columns (5) and (6) show negative binomial regressions where the dependent variable is the monthly count of well blowouts. The sample includes all firm-months with drilling activity. In Columns (3)–(6), the dependent variable is normalized by including the log of the normalizing quantity as a regressor with coefficient constrained to one. 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 $e^{\phi} - 1$. During the sample period, there were 299 firms that orphaned wells, 5,417 water protection rules violations, and 212 well blowouts. Standard errors are clustered by quarter. *** indicates statistical significance at the 1% level; ** at the 5% level; and * at the 10% level.

Table 8: The Effect of Increased Bond Requirements: Intensive Margin Effects

	Water Protection Rules Violations (Negative Binomial)		Well Blowouts (Negative Binomial)	
	(1)	(2)	(3)	(4)
$1[After]$	0.056	-0.180^{**}	-0.677^{***}	-0.964^{***}
	(0.084)	(0.170)	(0.160)	(0.277)
% Change in Expected Count	**6%**	**-16%**	**-49%**	**-62%**
Constant	-8.388^{***}	-8.223^{***}	-6.602^{***}	-6.297^{***}
	(0.072)	(0.155)	(0.089)	(0.244)
Time Trend	None	Exponential	None	Exponential
Month-of-Year FE	No	Yes	No	Yes
Normalization	Wells Operated	Wells Operated	Wells Drilled	Wells Drilled
N	455,566	455,566	44,128	44,128
Firms	5,026	5,026	2,826	2,826

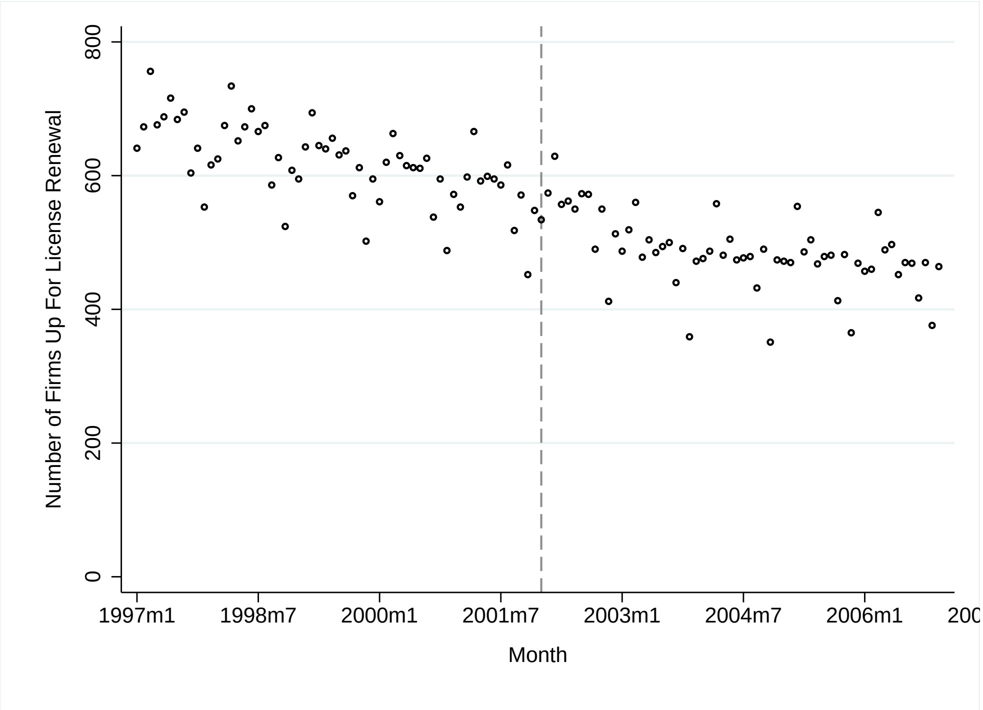
Notes: This table reports results for the specifications in Columns (3) – (6) of Table 7, after further limiting the sample to firms that entered the industry prior to December, 2001 and exited after January, 2003. See text for details on each regression. Standard errors are clustered by quarter. *** indicates statistical significance at the 1% level; ** at the 5% level; and * at the 10% level.

Appendix Figure 1: Net Entry (Entry - Exit) by Month



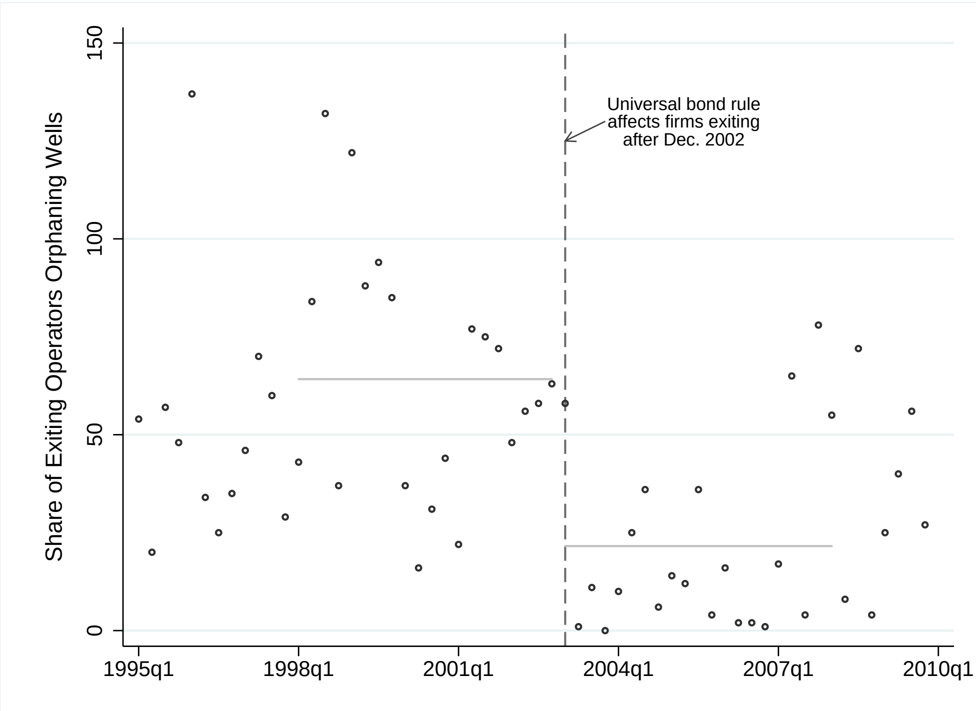
Notes: This figure shows the net change in the number of firms in the industry each month. Entry date is defined as the date of the firm's first annual operating license filing. Exit date is defined as 365 days after the firm's final annual operating license renewal. The sample includes all firms with oil or gas leases from 1990 to 2010. The initial rollout of the partial bond requirement occurred during September, 1991 to August, 1992. The initial rollout of the universal bond requirement occurred during January–December, 2002.

Appendix Figure 2: Number of Firms Up For License Renewal Each Month

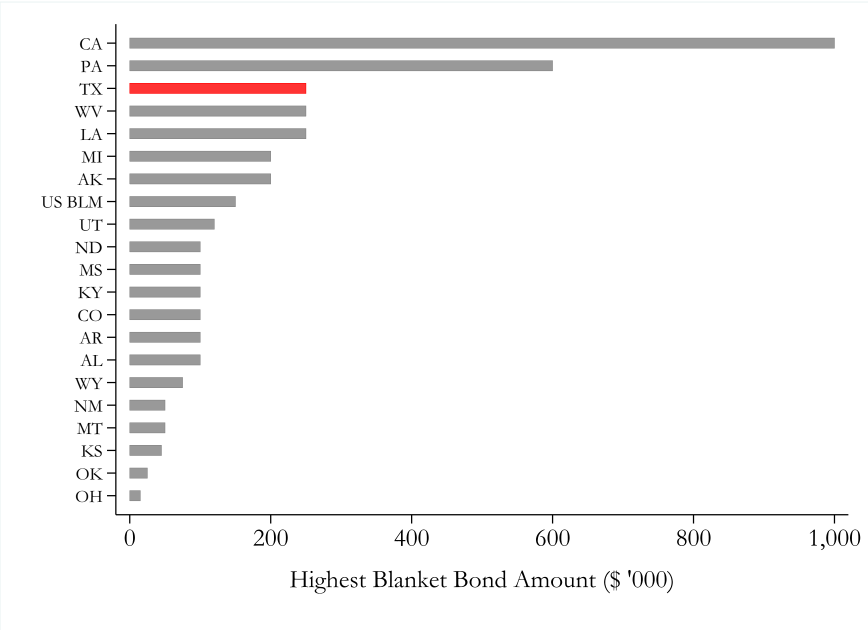


Notes: This figure shows the number of firms required to renew their annual operating license (or exit the industry) in each month. These months are assigned by the Texas Railroad Commission and cannot be manipulated by firms. The sample includes firms with oil or gas production during 1997–2006. The vertical dashed line indicates the implementation of the increased bond requirement in January 2002.

Appendix Figure 3: Number of Orphan Wells By Operator's Quarter of Exit



Appendix Figure 4: Bond Requirements By State



Notes: This figure shows the maximum required bond per firm in the 20 U.S. states with the most drilling activity in 2012, and the federal Bureau of Land Management. Information on bond requirements is from Penn Environment Center 2013. "Who Pays the Cost of Fracking?" http://pennenvironmentcenter.org.

Appendix Table 1: Comparing Firms by License Renewal Month

Month	(1) Number of Firms	(2) Mean Annual Production ($)	(3) Std. Dev. Annual Production ($)
January	769	1,450,156	5,388,415
February	791	1,409,704	5,358,007
March	874	1,451,261	5,476,291
April	784	1,156,730	4,729,774
May	760	1,157,181	4,271,193
June	807	1,429,897	5,545,757
July	763	1,037,615	4,085,928
August	773	1,165,920	4,312,536
September	673	1,414,795	5,316,751
October	734	1,001,681	3,812,794
November	609	1,334,588	4,806,508
December	684	1,487,344	5,198,563
F statistic		0.97	
p-value		0.47	

Notes: This table reports summary statistics for firms according to the month which contains their annual license renewal date. This table covers firms from their 1996 to 2000 license renewals. Annual production 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 noise caused by 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 2: Controlling Seperately for Crude Oil and Natural Gas Prices

	(1) **Quintile 1**	(2) **Quintile 2**	(3) **Quintile 3**	(4) **Quintile 4**	(5) **Quintile 5**
Begin Rollout	0.110***	0.122***	0.046**	0.047***	−0.018
	(0.017)	(0.028)	(0.019)	(0.014)	(0.014)
End Rollout	−0.153***	−0.114***	−0.091***	−0.050**	−0.011
	(0.032)	(0.022)	(0.019)	(0.019)	(0.015)
Oil Price	−0.080	−0.088**	−0.050	−0.037	0.047
($100/bbl)	(0.057)	(0.033)	(0.036)	(0.029)	(0.031)
Natural Gas Price	−0.508	0.072	−0.436**	0.095	−0.331**
($100/mcf)	(0.354)	(0.272)	(0.179)	(0.166)	(0.139)
Constant	0.177***	0.093***	0.085***	0.049***	0.102***
	(0.015)	(0.022)	(0.013)	(0.009)	(0.010)
N	11,903	13,267	14,667	16,197	15,792
Firms	2,129	2,185	2,202	2,226	2,236

Notes: This table is identical to table 3, except that crude oil and natural gas prices, which are highly correlated during this period, are both included in the regressions.

Appendix Table 3: Texas Railroad Commission 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)	**January 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.