An Evaluation of the Toxicity of Hydraulic Fracturing Injectants*

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Abstract

In the past 10–15 years, innovations in hydraulic fracturing and horizontal drilling have fueled a boom in the production of natural gas from geological formations that were previously unprofitable. The rapid deployment of fracking has been accompanied by concerns about negative externalities. In response, a regulatory regime has emerged that requires disclosure of chemical additives, but preserves a loophole by which firms can claim that such disclosure imperils "trade secrets." To shed light on the importance of such a disclosure rule, we combine data from wells drilled in two significant gas fields in Wyoming with disclosure data from FracFocus about injected chemicals and materials. We explore the relation between toxicity of injectants, tendency to use the trade secrets shield, and identity of the well operator and the service company that performed the frac job. Our results have implications for the impact on social net benefits of the recently reported merger between two major service companies.

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1 Introduction

Increased oil and natural gas production in the United States during recent years is largely attributed to technological change in extraction technology (Mason et al.; 2015; Hausman and Kellogg; 2015). Horizontal drilling and hydraulic fracturing, and perhaps more significantly, the combination of the two, have added huge reserves of unconventional resources once considered too costly to extract. Developing and mastering these technologies required both experiential and social learning (Covert; 2014). The experiential nature of the technology shock both created profitable investment opportunities and changed the competitive landscape for the oil and gas industry. The modern oil and gas industry is both technically sophisticated and fiercely competitive. We examine the competitive environment of the upstream oil and gas industry, in particular the interaction between operating firms and service companies. We study how the competitive environment affects possibilities for social and experiential learning.

The dynamic competitive environment forced oil and gas developers and their partners in the oilfield service sector to closely guard any perceived informational advantage. In order to maximize profits, firms seek to enhance production from wells that require fixed investments in both drilling and completion. While the productivity gains from relationships between operators and drilling companies have been documented (Kellogg; 2011), we are interested in the interaction between operators and service companies performing frac jobs.

The rapid deployment of fracking has been accompanied by concerns about negative externalities, including impacts to air and water associated with the chemicals used as injectants during the fracking process, or in the disposal of waste water. Concern about water contamination from hydraulic fracturing, even if such contamination has not (yet) been documented, has real economic consequences (Muehlenbachs et al.; 2015). Concern about environmental risk has led to public disclosure of some ingredients in hydraulic fracturing fluid. We examine the use of toxic additives to hydraulic fracturing fluid. Because of the competitive forces at play among developers and service companies, many hydraulic fracturing additives are not disclosed to the public, but instead are shielded by a nondisclosure provision. As firms compete within the industry, we are interested in possible spillovers to environmental risk. These concerns underscore the recently released federal rules governing fracking;[1] one important element of these new rules is the stipulation that firms report all injectants used in the frac job.

The technological shift in natural gas production has important impacts on U.S. markets, generating important benefits to consumers and producers alike. This transformation also has great potential to curtail the use of coal in power generation, and thereby lower greenhouse gas emissions (Knittel et al.; 2015; Fell and Kaffine; 2015). Our empirical application is in the western tight sand formations of Sublette County, Wyoming. This allows us to focus on fracking in isolation from horizontal drilling, because the wells we study are (nearly) vertical. Western tight sands are distinct from shale formations, which have received considerable attention in news media.

We estimate a production function for hydraulic fracturing. This allows us to identify three different types of impacts. First, we observe how the physical characteristics of frac jobs change over our sample period, in terms of both scale and scope. This allows us to estimate the marginal production effects of hydraulic fracturing. Second, because we know the firms involved in each well, we can observe how firm behavior changes over the course of time. In particular, we are interested in how firms perceive the value of withholding disclosure of the ingredients in their frac jobs. We are also able to objectively assess the productivity of wells with differing levels of disclosure. These different measures allow us to

[1]See 43 CFR §3160, added 26 March 2015. Federal Register 80(58) 16128–16222.

characterize the strategic environment in which firms operate. Third, we observe differing levels of toxicity in various parts of the fracturing fluid, and we can assess trends in use of toxic ingredients. Because public concern about environmental risks has focused on the toxicity of injected fluids and produced water, an assessment of the role of toxic additives will help inform the policy debate.

2 Background

2.1 Hydraulic Fracturing

Although often conflated if not confused, drilling and hydraulic fracturing are separate processes. Drilling can be vertical, directional, or horizontal. Fracturing is performed with specialized pressure pumping equipment, usually after the drilling rig is removed. The wellbore is perforated in a target formation. To focus available pumping power on isolated sections of the wellbore, the pressure pumping often occurs in stages, with each stage focusing on a portion of the perforated wellbore. A slurry of base fluid (usually water), proppant (usually sand), and chemical additives is mixed on the surface. The pressure pumps then force the slurry into the target area, creating fractures in the rock. As pressure is reduced, proppant remains in the hydraulically-created fractures, leaving a pathway for oil and gas to migrate to the wellbore and then to the surface. Oil and gas molecules that would otherwise be trapped in the rock can thereby be produced.[2]

Each frac job has many variables: the amounts of water and sand, the maximum pressures and duration, and the combination of additives to the "secret sauce." The additives are intended to enhance performance of the fluid in one or more dimensions, for example by reducing friction or increasing viscosity. Reducing friction allows more fluid to be pumped

[2]For a non-technical discussion of the emergence of the fracking technology in conjunction with horizontal drilling as a method for enhancing hydrocarbon production from low permeability reservoirs, see Gold (2014).

by fixed pressure pumping horsepower; higher viscosity allows more proppant to be carried in a fixed amount of fluid. Because fluid chemistry is an important part of the fracturing process, the recipes for fluid are viewed as important proprietary assets, especially by service companies. Service companies advertise various recipes and consulting expertise to operating firms.

A substantial technical literature addresses aspects of fracture design and implementation. For our purposes, we focus on two stylized facts. The first is that fracture designs continue to evolve. Patel et al. (2014) compares the time trends in frac fluid and proppant design in the Marcellus, Bakken, and Denver-Julesburg plays. In each of these locations, firms have continued to experiment with alternative proppants and worked to increase the amount of proppant delivered. The second stylized fact is that alternative fluid configurations are used in different areas. This makes cross-sectional analysis of fracturing fluid difficult. What works in the Marcellus may be totally inappropriate in the Bakken. This leads us to focus on a single play, where we use relatively small variation in fracturing fluids and designs to identify differences in production.

2.2 Previous Work

Studies of the effect of technical change on marginal productivities in oil and gas are somewhat limited, with much of the literature instead focusing on industry-level total factor productivity (Cuddington and Moss; 2000). Chermak and Patrick (1995) focus on the role of information technology improvements on extraction costs for natural gas. More efficient well completion is one of the key pathways for productivity gains. The literature has largely ignored strategic considerations.

Chermak et al. (2012) is a previous study investigating the production outcomes associated with alternative frac jobs. Our sample is larger and from a single county with less geologic variation, which attenuates concern about omitted variables.

Covert (2014) examined the experiential and social learning by well operators in the Bakken shale of North Dakota. Our study expands the scope to include service companies. Our application is in a tight sand formation where natural gas is the primary target as opposed to petroleum in the Williston Basin shales.

Financial impacts of the natural gas boom have been notable. Gilje et al. (2015) estimate that 20–25 percent of the increased market capitalization in U.S. equity markets since 2009 can be attributed to shale oil development enabled by hydraulic fracturing.

Hydraulic fracturing and high natural gas prices in the 2000s made many more wells economically viable. Development spread from a few areas that were largely accustomed to oil and gas operations across the country, and into areas with residents who were more skeptical of the new activity. Mason et al. (2015) highlight perceived risks of both surface and groundwater contamination from expanded operations as most germane to the toxicity of fluids injected in the fracturing process, and management of flowback and produced water. Concerns over contamination from these pathways helped provide the impetus for public disclosure of hydraulic fracturing fluids. Initial efforts to promote disclosure were resisted by firms active in the industry, especially service companies concerned about revealing proprietary information (Wiseman; 2011)

2.3 Toxicity

Centner (2013) overviews the issues of toxicity surrounding proliferation of hydraulic fracturing in the United States. Stringfellow et al. (2014) evaluate the toxicity of various common ingredients in fracturing fluid. We use their analysis to help characterize both the hydraulic fracturing production function and the toxicity of various ingredients. We also use information about workplace toxicity hazards to enumerate toxicity of various compounds. Esswein et al. (2014) highlight the risks for oil and gas employees (who presumably receive a compensating differential for known risks incurred in the course of oilfield work).[3]

2.4 Oilfield Service Companies & Operators

Oil and gas developers drill wells and produce the hydrocarbons with technical assistance from an array of contractors including drillers, pipeliners, and service companies. Platt and Platt (1989) showed the strong interrelationship between oil and gas producers and oil and gas field service companies—not surprising given that the service industry relies on upstream investment by developers. As unconventional resources have become more important to the U.S. reserve base, service companies have assumed an important role in well completions and hydraulic fracturing. The well servicing industry has historically been highly concentrated.[4]

Given the interdependence between the two types of firms, and the potentially strategic environment fraught with environmental risks, the governance of the relationship between these firms is an important consideration. Operators and service companies interact in repeated games. Corts and Singh (2004) studied the use of alternative contracts between developers and drillers in an offshore context; their results suggest that transaction costs are minimized by using weaker (day rate) contracts, but that repeated interaction is important to the success of the relationship. Kellogg (2011) found similar results in the onshore drilling context. Strong productivity gains from repeated interaction help explain the prevalence

[3] We are agnostic about whether the right measures are for ambient toxicity or exposure to workers. While the latter seems more likely to occur, the former has a stronger rationale for intervention as a market failure. We use the OSHA database because it is more accessible than alternatives like the EPA IRIS database.

[4] The 2012 Economic Census for NAICS 213112 indicates a total of 9,621 establishments in this category, which covers 71 activities. Hydraulic fracturing is only one of these activities. Rogers (2011) reports a 75 percent market share for the three largest service companies in the pressure pumping market, roughly contemporaneous with the beginning of our data.

of long-term weak contracts between drillers and developers.

We are interested in the relationship between developers and service companies. While the previous results regarding drillers are suggestive, we have no direct information about contracts specific to each well. Anecdotal evidence suggests that stronger fixed price contracts are prevalent in this context, despite the opportunity for repeated interaction. Fitzgerald (2015) provides some evidence that strong productivity gains are not as likely between developers and service companies, which would help explain the use of strong contracts. With strong contracts firms should try to differentiate products for higher profits, and fluid chemistry is one margin for differentiation.

Well operators are required to report activities to the Wyoming Oil and Gas Conservation Commission (WOGCC). In the case of exploratory or "wildcat" wells, operators are able to keep records confidential for up to six months.[5] This is clearly an opportunity for an operator to behave strategically and withhold information from public purview, at least for wildcat wells. If wells begin producing, operators are not able to extend this confidentiality. Our data were collected well after the completion of the wells in our sample, and focuses exclusively on producing wells. We are not able to observe if wells in our sample were confidential at some earlier point in time.

3 Model

3.1 Production

We are interested in the production of a composite hydrocarbon designated y that is generated by a multivariate hydraulic fracturing process. The functional form of the process is unknown to us, but we posit that the production from a given well depends on the footage

[5] W.S.C. Ch. 3 §21 (d)

of wellbore (z) that is exposed and treated by hydraulic fracturing:

$$y = Af(x_1, \ldots, x_n, z) = Az^k F(\frac{x_1}{z}, \ldots, \frac{x_n}{z}), \tag{1}$$

where $x_i, i = 1, \ldots, n$ are a set of ingredients used in the frack job. This expression of the technology has the desirable property that f is homogeneous of degree k even as the properties of F are not restricted. Our production function is therefore best thought of as a frac per foot function.

Although we are unsure about the true form of F, for expositional concreteness we suppose the technology is Cobb-Douglas. While this functional form makes strong separability assumptions, it has the advantage of analytic convenience.[6] For each injectant $i = 1, \ldots, n$, we define $X_i = \frac{x_i}{z}$. Then

$$y = Az^\gamma \prod_i X_i^{\alpha_i} \tag{2}$$

Logarithmic transform of eq. (2) yields:

$$ln(y) = \beta lnA + \gamma ln(z) + \sum_i \alpha_i ln(X_i). \tag{3}$$

We suppose the productivity parameter A depends on a variety of factors that have been documented to affect production in other geological contexts (Covert; 2014). Specifically, we assume

$$A = exp(CONSTANT + AGE + SIZE + SANDRATIO) \tag{4}$$

The AGE of a well is included to capture the reality of geophysical decline in production over time. The other two variables capture scaling effects: $SIZE$ is a measure of the total

[6]Note that the separability is across categories. Within categories alternative ingredients are effectively perfect substitutes.

volume injected on a per foot basis, and $SANDRATIO$ controls for fracs with a greater or lesser amount of proppant per unit of volume injected.

The final step is to specify the relevant categories of additives in eq. (1). There are hundreds of different observed additives, and so to facilitate the empirical analysis greatly we aggregate into six categories: biocides, breakers and crosslinkers, chemical additives, gelling and foaming agents, surfactants, and all other ingredients.[7] Biocides ($BIOCIDE$) are used to kill bacteria that might clog the wellbore and impede flow. Because their purpose is to kill microorganisms, the compounds that are used can be harmful to humans. Breakers and crosslinkers ($BREAKER$) are some of the most technically important additives. Crosslinkers increase viscosity of fluid to increase the amount of proppant that can be transported by fixed pumping capacity. However, the crosslinking must be reversed to recover fluid and leave proppant in place, so chemical reactions triggered by breakers, often after some delay, are used to reverse the process. The chemical properties of injected fluid are critical and must be tailored to the conditions specific to the borehole (pressure, temperature, salinity, presence of other chemicals). Companies use a variety of chemical additives ($ADDITIVE$) to control clay and iron deposits, prevent corrosion or scaling of production tubing, and balance the pH of the fluid. To create a high viscosity fluid, firms mix various gelling or foaming agents (GEL) to help transport proppant. In an effort to reduce friction and ease the burden on pumping equipment, friction reducers and surfactants ($SLICKS$) are added to the fluid. Some of these additives are oils similar to those that are targeted for production. Finally, although we have detailed information about each well, there are some additives that we are unable to place into one of the categories described above. We keep these leftover ingredients in their own category ($UNSPECIFIED$).

[7] In addition, frac jobs use proppants and water; these are included separately in our specification.

3.2 Strategic Interaction

As operators compete in competitive output markets, they have a choice of differentiated completion inputs provided by different service companies. One argument for product differentiation among service companies is to relax pressures to compete on price in the factor market. If service companies cannot price discriminate, profit maximization dictates zero product differentiation. Anecdotally, service companies are able to price discriminate, which implies that product differentiation should be greatest to support this outcome. Service companies could differentiate their products in a number of ways, but adjusting the fracking recipe is one obvious mechanism. To the extent that service companies promulgate uncertainty about their respective product mixes, they are able to enhance market power (Carlton and Perloff; 2008).

4 Data

Our analysis relies on data drawn from four sources. First, we used well-specific records extracted from the FracFocus repository to document what was injected in each of wells completion. Second, we used completion reports (Form 3) from the WOGCC, the primary regulator of oil and gas operations in the state, to augment the FracFocus data with additional information about the frac jobs. The completion reports allowed us to cross-validate the FracFocus data on injected substances, as well as add information about technical aspects of each frac job. Third, we matched the specific injectant data from FracFocus to information about toxicity of the substances using the OSHA Occupational Safety Database. This allows us to comment on the potential for environmental spillovers. Fourth, we used production reported at the well-month level to assess the ultimate production of alternative fracking techniques. These data were compiled by private data provider

DrillingInfo.

FracFocus is a joint venture of the Interstate Oil and Gas Compact Commission and Groundwater Protection Council (`http://www.fracfocus.org`). Since 2010, FracFocus has published company-provided data on hydraulic fracturing jobs across the country. In some states, FracFocus has satisfied state-level disclosure regulations; in Wyoming, the WOGGCC maintains a similar but separate registry for legal disclosure purposes, but it is not available to the public. In Wyoming, all wells with drilling permits issued after August 17, 2010 were subject to disclosure.[8] The FracFocus database has been revised through three versions, and we use data from each version. The information disclosed in each version of the FracFocus database has changed slightly, so we were careful to extract similar information from all versions. EPA (2015) has provided a detailed analysis of the first version of the database.

Operators are required to file Form 3 with the WOGCC after a well is completed and each time a well is recompleted. We dropped recompletions from our production analysis, but kept them for toxicity analysis.[9] Appended to these reports are detailed information about frac design and implementation. We use these information to characterize technical aspects of the completion, including the number of stages and the footage of the treated interval.

The OSHA Occupational Chemical Database (`https://www.osha.gov/chemicaldata/`) includes 751 chemical compounds that are considered potentially hazardous. The database was originally compiled in cooperation with the Environmental Protection Agency. Compounds are indexed by unique chemical abstract service (CAS) numbers. Because these same unique identifiers are reported in FracFocus records, we are able to match the com-

[8]If firms value avoiding disclosure, a natural concern is that firms timed permit application for approval *before* the policy went into place. This does not appear to be the case. The modal day for permit approval in all of 2010 was August 18, the day *after* the policy went into effect.

[9]This results in dropping nearly all wells from one operator.

pounds directly. The database also reports exposure guidelines. In cases where we were unsure about a compound, we referred to the National Institute for Occupational Safety and Health pocket guide to clarify. Despite this cross-referencing, there were numerous compounds that we were not able to identify by reported name or CAS number. Our maintained assumption is that any such compounds are not toxic hazards. Similarly, because operators can elect not to disclose the CAS number of certain additives that they deem are proprietary business information, we are unable to assess the toxicity of undisclosed additives. We conduct separate analyses along this dimension.

The bottom line for oil and gas producers depends on the amount of natural gas and oil produced. In order to measure these outcomes, we turned to well-specific production data provided by DrillingInfo (`www.drillinginfo.com`). These data are derived from operator reports of well-level production. Production can be aggregated in several different ways. In our preliminary results, we use aggregate production over the first 6 or 12 months of a well's life. We acknowledge that some elements of frac design may be targeted at increasing peak flow, or maintaining higher flow rates over time. We provide initial panel to examine dynamic effects.

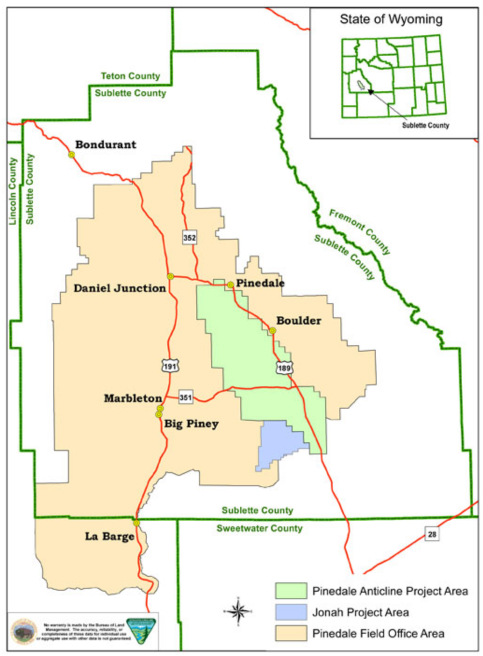
4.1 Oil and Gas in Sublette County

Oil and gas has been part of the Sublette County landscape for decades, largely focused on the western edge of the county near the communities of Marbleton and Big Piney (see figure 1). The earliest well on the Pinedale Anticline was drilled in 1939, but it targeted oil and was plugged when it instead found natural gas. By the early 1990s, advances in exploitation of western tight sands made the geology of Sublette County more attractive.[10] Exploratory efforts led by McMurray Oil Company (but including several other firms)

[10] Fracking of vertical wells was common at this point in time, although the designs were far different and smaller in scale than more recent application of the technology that we investigate.

helped the Jonah and Pinedale Anticline became economically viable. Thanks largely to successive expansions in pipeline capacity between the production areas and the Opal trading hub, which were completed between 1996 and 1999, production of both oil and natural gas expanded rapidly during the first years of the 2000s. Figure 2 shows the increase.

Figure 1: Sublette County, Wyoming

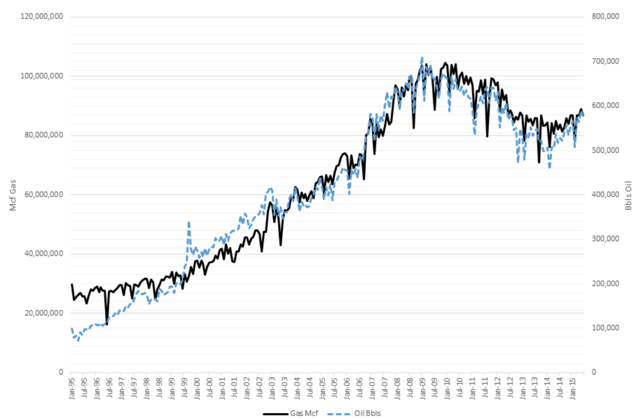


Source: Pinedale Anticline Project Office, Wyoming BLM

The rapid expansion of production in Sublette County was affected by its remote location. As production increased, insufficient infrastructure was in place to transport natural gas to markets, both locally and over a longer distance. The proximity to the important gas marketing hub, at Opal, was not sufficient to keep prices received by producers high, or even in line with national benchmarks (Oliver et al.; 2014).

An overwhelming majority of the wells in Sublette County are located on federal surface and minerals, and are therefore subject to federal environmental oversight as administered by the Bureau of Land Management (BLM). A very small fraction of wells are located on private minerals, with the balance on state-owned surface and minerals. These wells are subject to environmental regulation by the state of Wyoming. During the period we study, federal agencies had no rules pertaining directly to fracking, so state rules covered both.

Figure 2: Oil and Gas Production in Sublette County



Source: WOGCC

4.2 Descriptive Statistics

We have detailed completion and production information from a total of 569 wells in Sublette County, but limit ourselves to only wells with full completion data (both FracFocus and WOGCC completion reports). We also exclude wells that have been fracked more than once. Our analysis focuses on about 200 wells in the most limited samples. These wells are primarily drawn from two adjacent western tight sands plays—the Jonah field and the Pinedale Anticline.[11]

[11]While these two plays are geograhically separate, and differ in some technical details, they are located within a common leasing and well servicing market. Moreover, most of these wells are accessing the same

As operators hire service companies to frack wells, both parties may experience gains from learning-by-doing. Contemporaneously, firms may observe other experiments and tweak their own fracking formulae to increase production. Table 1 summarizes the key completion choices made by firms.

Table 1: Summary Statistics for Frac Jobs

	Mean	Std. Dev.	Min	Max
H_2O Volume (gal)	1,562,927	1,010,253	364,433	5,614,448
Sand/Water Ratio	0.149	0.070	0.023	0.370
Ingredients (count)	84.590	11.659	28	90
Stages	15.65964	4.871937	3	27
Treated Interval (ft)	4,381.538	1,475.933	0	6,324
Total Depth (ft)	13,424.44	871.2958	10,491	14,914

Notes: Data compiled from FracFocus records and WOGCC completion reports. N=333

Given the variety of frac designs that are used in our sample, one important question is how withheld additives, or trade secrets, are used. Table 2 summarizes the use of trade secret provisions across the categories of fluid ingredients.

Many of the ingredients that we see in injection reports do not match with compounds analyzed by Stringfellow et al. (2014), and we therefore have a difficult time categorizing them.[12] The unclassified category is the most common category for trade secrets, followed by biocides used to control subsurface bacteria.[13]

underlying gas-bearing formation (the Lance). Accordingly, we believe it is appropriate to combine the two plays in our analysis.

[12]For compounds that we observed in other wells, we used the modal purpose in the other data to help classify ingredients by purpose. Nonetheless, we have many unclassified additives.

[13]Kahrilas et al. (2014) study biocides specifically, and we use their analysis to confirm categorization.

Table 2: Number of Ingredients Withheld as Trade Secrets

	Mean	Std. Dev.	Min	Max
Additive	0.688	1.251	0	4
Biocide	1.102	1.597	0	4
Breaker	0.583	0.820	0	3
Gel	0.375	0.707	0	3
Slicks	0.577	0.739	0	2
Unspecified	1.748	2.073	0	6
Total	5.111	5.710	0	16

Notes: Estimation sample only. Data compiled from FracFocus records. N=333. Total includes undisclosed proppants.

Because we observe well completions over a period of four calendar years, we tested to see if there is a trend in claims of secret additives. We did not find a significant trend over time. There are, however, significant differences across firms–both operators and service companies.

Disclosure of the fluid ingredients reveals to the public and potential competitors what is in the "secret sauce." The FracFocus records provide information about the concentration of each ingredient in the additive, and in the final fluid that is injected. This makes it hard to back out exactly how to mix the fluid, but provides enough information to expect what concentration of a given additive is likely to be in the fluid (if, for example, an interested person wanted to know what calibration was needed to detect the presence of a particular chemical compound). As a great chef knows, ingredients are important, but the precise measurement and the practice of how they are combined is at least as important as knowing the identity of each component. The recalcitrance of some firms to reveal the ingredients has exaggerated concerns about the environmental risks associated with those additives.

There is an apparent tradeoff between the trade secrecy and disclosure of a CAS number and associated toxicity. Recall that undisclosed additives cannot be assessed for toxicity using our methodology. A firm might have a number of motivations for invoking a trade secret. One reason is that a firm may consider a particular additive a critical ingredient that dramatically boosts well production. In order to maintain an edge in the marketplace, the firm might be unwilling to reveal its particular recipe for fracking. Alternatively, a firm might simply be experimenting with a new formula, and wishes to conceal the experiment and its outcome from any potential competitors. Third, and non-exclusively, a particularly toxic additive could be kept out of public scrutiny by protecting it with a confidential label. Weighing the various arguments for and against the disclosure of a particular additive is likely to vary at the firm level, as competitive position and views on corporate liability might vary.

Using our measure of toxicity, table 3 summarizes the number of additives, by category, that are indicated to have toxicity hazards. It is important to remember that withheld additives (protected as trade secrets) are not included in these measures.

Table 3: Number of Toxic Ingredients

	Mean	Std. Dev.	Min	Max
Additive	1.811	1.025	0	4
Biocide	0	0	0	0
Breaker	1.919	1.438	0	7
Gel	1.195	0.691	0	3
Proppant	1.961	1.299	1	8
Slicks	0.294	0.456	0	1
Unspecified	0.243	0.524	0	3
Total	7.440	3.258	2	17

Notes: Estimation sample only, with undisclosed additives excluded. Data compiled from FracFocus records, as matched to OSHA Occupational Safety Database. N=333.

As expected, two of the most toxic categories of additives are gels and breakers or crosslinkers, which used to adjust fluid viscosity (upwards for injection, then downwards for fluid recovery). More of a surprise is that proppants are more often matched to toxic substances than many other compounds. Certainly sand and ceramic proppants are not often thought to be the greatest environmental hazard in frac fluid. However, many operators do treat the proppant, such as coating it with resin; and the coating may be in the OSHA database. Chemical additives used to balance pH or other properties of the fluid, because they are often strong acids, are unsurprisingly also common on the toxic list.

Production is the ultimate goal of every well. Sublette County is predominantly a natural gas province, but some oil and other valuable liquids is co-produced with the gas. For that reason we consider both raw (dehydrated) gas production and total production on a barrel of oil equivalent basis. Sublette County wells produce some oil along with the gas, as well as valuable natural gas liquids (see figure 2).[14] Table 4 summarizes the production statistics that we use in our cross-sectional analysis.

Table 4: Summary of Production Measures

Measure	Mean	Std. Dev.	Min	Max
Aggregate Natural Gas (Mcf)				
First 6 Months	358,979	171,266	10,591	1,060,576
First 12 Months	579,802	250,742	11,554	1,693,901
Aggregate Oil Equivalent (BOE)				
First 6 Months	63,112	29,500	1,921	177,155
First 12 Months	102,055	43,357	2,082	287,199

Notes: Data provided by DrillingInfo. N=333.

We do not observe prices at which output was sold, so it is not clear how long an average

[14] These products are generally not priced on an energy equivalent basis, but the conversion to BOE is useful to consider alternative measures of production.

well must produce before drilling costs are recovered. As mentioned above, large basis differentials for western Wyoming are likely to affect the economic value of production.

4.3 Important Differences Amongst Firms

The wells in our sample were operated by four firms at the time of completion, one of which has only a handful of the wells that we observe. The well completions were provided by three different service companies.[15] Table 5 summarizes the frequency of pairings between the operators that we observe and the service companies.

Table 5: Pairings of Operators and Service Companies

	Service Company			
Operator	A	B	C	Total
I	19	0	239	258
II	0	226	0	226
III	64	0	0	64
IV	0	17	4	21
Total	83	243	243	569

Notes: Compiled from WOGCC reports, FracFocus records, and DrillingInfo.

In our estimation sample, service companies A and B have roughly equal positions in the local market, each with about 30 percent of the wells. Company C has a larger stake of about 40 percent. The concentration among the operating firms is parallel—two smaller firms with roughly equal shares, and one larger firm. The table also reveals the specificity of relationships between operators and service companies. Operator II exclusively uses service company B, but each of the other operators uses two different service companies.

Given our interest in both strategic interactions and toxicity of additives, we explore the data along those dimensions. We find significant differences in how different firms employ

[15] In some cases subcontractors assist the primary service company or provide some services that we can observe. For the purposes of our analysis, we focus on the three major service companies.

both trade secret provisions and toxic additives.

Table 6: Summary of Trade Secrets and Toxicity, per Well by Service Company and Operator

	Trade Secrets				Toxic Additives			
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Service Company								
A	1.769	1.068	0	8	5.538	2.432	2	15
B	12.920	4.475	0	16	10.483	1.576	7	17
C	2.608	3.266	0	9	6.717	3.200	2	16
Operator								
I	2.541	3.202	0	9	6.939	3.198	2	16
II	13.422	3.892	1	16	10.277	1.233	7	13
III	1.762	0.429	1	2	4.619	1.430	2	9
IV	2.500	2.887	0	5	14.750	2.062	13	17

Notes: Data compiled from FracFocus records, as matched to OSHA Occupational Safety Database. Total N=331.

While there are large differences across service companies and across operators, it is not clear from table 6 which type of player – operator or service company – is making the decision not to disclose particular additives. There is a motive for the service company (the seller in this relation) to obscure the mix used in the frack job, so as to enhance its market power (Carlton and Perloff; 2008); this observation suggests it is the service company, and not the operator, who is electing to withhold some ingredients. On the other hand, ultimate responsibility for the well, including liability for environmental consequences, rests with the operator, in which case it would be in that party's interests to create an air of obfuscation. Under these circumstances it might also be beneficial for the operator to allow the public think that service companies are keenly interested in protecting trade secrets.

5 Empirical Strategy

5.1 Production Outcomes

Our detailed data allows us to estimate a variant of eq. (3). Because we have an aggregate production measure as the dependent variable (whether over 6 or 12 months), our initial empirical specification is a cross-sectional analysis.

$$lny_j = \beta_0 + \beta_1 WATER_j + \beta_2 SANDRATIO_j + \beta_3 lnFOOTAGE_j + \sum_i \alpha_i lnX_i + \varepsilon_j \quad (5)$$

We use the log of total base fluid injected as the basis for $WATER_j$. We use the footage of the treated interval for $FOOTAGE_j$.[16] For every well we also know the location, service company, and the operator at the time of the completion.

We are also interested in toxicity. Because it is hard to measure toxicity directly, we interact the aggregate toxicity in each additive class with the amount. To simplify the notation, we collapse the other independent variables as in eq. (4),

$$lny_{jt} = \beta' A_j + \sum_i \alpha_i lnX_i \times TOXIC_i + \varepsilon_{jt} \quad (6)$$

The interpretation of the α_i in this specification is as weighted least squares, with the categorical toxic additive counts as weights.

When we are interested in strategic behavior by operators and service companies, we substitute disclosure shares for the toxicity measure in eq. (6).

$$lny_{jt} = \beta' A_j + \sum_i \alpha_i lnX_i \times SECRET_i + \varepsilon_j \quad (7)$$

[16] Because we exclude wells that are refractured, the treated interval is constant. It is possible/likely that some of the refracs are "zipper fracs," in which the treated interval does not change.

The interpretation of the α_i in this specification is similar to that in eq. (6).

Because we have data on monthly production at each well, we estimate a well-month panel specification.

$$lny_{jt} = \gamma AGE_{jt} + \beta' A_j + \sum_i \alpha_i lnX_i + \varepsilon_{jt} \tag{8}$$

The variable AGE_{jt} measures the number of months well j has been actively producing as of time t. Accordingly, the parameter γ can be interpreted as the monthly decline rate in production. To the extent that characteristics of the frac job affect the decline rate, interacting those measures with AGE_{it} will provide inference about the dynamic effects.

5.2 Toxicity and Secrecy

In addition to understanding the roles of various disclosed and undisclosed ingredients in the productivity of fracking recipes, we examine the toxicity and secrecy of additives in their own right. These regressions identify broad trends in the employment of trade secret provisions to avoid disclosure, and in the use of identifiable toxic additives. We investigate the sum of all toxic additives, irrespective of the purpose.

$$\sum TOXIC_i = f\left(A_i, SECRET_i, OPERATOR_i, SERVICE_i, YEAR_i\right) \tag{9}$$

Because the data are inherently counts, our primary model for f is Poisson, but we also estimate negative binomial and OLS specifications for comparison.

6 Results

We begin with exploratory specifications in table 7, which report variants of eq. (5) for alternative production measures. The first two columns report regressions in which gas produced in the first six months of production is the dependent variable. Our measures of fracking recipes are jointly, but not individually, significant. This is true for each of the alternative dependent variables.

By way of comparing the specification, table 8 reports alternative specifications using the first 6 months' of gas production as the dependent variable (column 1 in table 7 is exactly the same as column 1 in table 7). We find no evidence of significant time trends in production over the period we observe wells and frac jobs. We do find some evidence of mean differences between operators and service companies, which is not surprising given tables 6, A.2, and A.3. We also find evidence of spatial variation in production throughout the county.

Turning to estimates of eq. (6), we report the results of exploratory specifications in table 9. While jointly significant, we again find limited evidence of greater toxicity significantly enhancing production, except for perhaps through friction reducers. Estimates of eq. (7) are reported in table 10. We have joint significance for the trade secrets, but no individual significance except again the case of friction reducers.

Because natural gas production extends over a period of time, adjusting the frac job to improve production over time may provide greater returns than other efforts at product differentiation. Table 11 presents results of panel regressions along the lines of (8). Here we find steep decline rates (7.5 percent per month), but not much evidence that they are directly affected by fluid additives as we measure them.[17] Nor do toxicity or trade secrets have a lot of purchase in these specifications.

Estimates of eq. (9) are reported in table 12. The first column lists the regressors used in these regressions. Included here are the number of three classes of ingredients whose identity is withheld under the trade secret exemption: gel, slicks and "unspecified." We also include indicator variables for operators I and II, along with service companies A

[17] This implies an annual decline rate of more than 50 percent when decline is restricted to be constant over the life of the well.

and B. With this specification, the default observations are based on service company B and operators III and IV; the parameters should be interpreted as identifying differences between the firm in question and the default.[18] For example, the estimated parameter on Service Company A indicates the difference in the average estimated number of toxic ingredients for A vs. B; the parameter on Operator I shows the difference in the average estimated number of toxic ingredients of I vs. III and IV. We also include indicator variables for the year the well was completed; here the default is 2010. Accordingly, the estimate associated with a year shows the difference in the average estimated number of toxic ingredients between that year and 2010. We believe this comparison is interesting, as Wyoming's reporting regulation took affect in 2010. As such, these coefficients allow one to assess the accuracy of a claim made by former Governor Freudenthal.[19]

We also include the number of stages, since a frac job with a greater number of stages offers the potential to use somewhat different mixes at different points in the well completion. We also include information on the ratio of sand to water and the total volume of water, as these values are crucial decision variables for the well completion, as our earlier results indicated.

We offer results from three regression models. The results in column 3 are based on an ordinary least squares (OLS) regression; we believe these should be viewed as a sort of benchmark, since this is a widely understood regression technique. The difficulty in this particular setting is that the left-side variable, the number of toxic ingredients reported for a particular frac job, is not symmetrically distributed; as such, it is unclear the data are compatible with the Gauss-Markov assumptions, and this calls into question the appropri-

[18] We exclude both Operator III and IV because one firm has only two observations in the reported specification.

[19] The former governor was fond of saying that before the regulation took effect, firms used diesel oil in their frack jobs, but that after the regulation was in effect they used salad oil. While an obvious oversimplification, the central point was that the regulation pushed firms to use less toxic mixes in their frac jobs. Our inspection of the raw reports leads us to view the Governor's claims with circumspection.

ateness of OLS. There are two oft-used alternatives in this sort of setting, both of which treat the left-side variable as a count variable. They are both taken from a particular family of regression models, often called count models; the more general of these is the Negative Binomial model (which we report in column 2), while the more specific variant in the Poisson model (reported in column 1). These models differ by virtue of the inclusion of a variable that captures individual heterogeneity in the negative binomial specification (whichwe call "Individual" in the first column); in the Poisson model, the coefficient on this regressor is constrained to equal zero.

Our results point to some broad conclusions:

1. First, the volume of water used in the frac job is inversely related to the number of reported toxic ingredients; that is, frac jobs that use more water tend to include fewer additives that are toxic. We are not able to address the concentrations of the additives in the final injected fluid in these specifications. In light of the multiple demands on water in the basin – it is an agricultural region, as well as the headwaters of the Green River, a major tributary to the Colorado, which is the most important river system for the western United States – this result takes on added significance. It points to the tradeoff between water uses, and suggests real value in technologies that might reclaim some of the water outflow from the well, often called "produced water," for alternative uses.

2. Second, wells fracked with a larger ratio of sand to water tend to contain more toxic ingredients. One explanation for this result is that a key use of the various ingredients is to facilitate the transit of the sand, or proppant, into fissures in the host rock. Evidently, the companies involved in frac jobs here deem this task better performed by ingredients that are relatively more toxic.

3. Third, a consistent result we obtain is that increases in the number of ingredients in the gel or slicks categories tend to increase toxicity, while increases in the number of ingredients in the unspecified category tend to decrease toxicity; while these effects are statistically important, they are not large in magnitude, calling their economic significance into question.

4. The fourth set of results we obtain are related to the firms involved in the wells. With respect to operators, we see a statistically important increase in the number of toxic ingredients associated with frac jobs undertaken on behalf of Operator I, as compared to Operators III and IV; by contrast, Operator II is associated with a smaller number of toxics than operators III and IV. With respect to the service companies, we see that service company B is associated with more toxic ingredients then either service company A or C; these differences are both statistically and economically important.

5. Fifth, the number of toxics associated with wells completed in wells 2012 and 2013 are significantly larger than wells completed in 2010; there is no difference between wells completed in 2011 and 2010. This observation casts doubt on Governor Freudenthal's witticism that the regulation enacted in 2010 induced firms to become more cautious about using toxic ingredients in their wells.[20]

6. Finally, the coefficient on "Individual" (the heterogeneity parameter) in column 2 is statistically important. One can interpret this result as evidence that the negative binomial specification is preferred to the Poisson model. But given the broad-based similarity between the results reported in columns 2 and 3, it is not apparent that

[20] Of course, it is possible that the regulation induced a decrease over time in the tendency to withhold ingredients, with some of the associated increase in reporting mapping into an increase in the number of reported toxic ingredients. When we estimate similar specifications substituting the number of withheld additives for the number of toxic additives, we find a strong downward trend in the number of trade secrets over time.

this distinction between distributions is critical.

7 Conclusion

In the past 10-15 years, innovations in hydraulic fracturing and horizontal drilling have fueled a boom in the production of natural gas (as well as oil) from geological formations – primarily deep shales – in which hydrocarbon production was previously unprofitable.[21] Impacts on U.S. fossil fuel production and the U.S. economy more broadly have been transformative, generating important benefits to consumers and producers alike (Mason et al.; 2015; Hausman and Kellogg; 2015). The widespread use of this new extractive technique also has great potential to expand the role of natural gas in U.S. energy markets, which presents an opportunity to curtail the use of coal, and thereby lower greenhouse gas emissions (Knittel et al.; 2015). Despite these potentially large benefits, the emergence of fracking has caused significant public anxiety, most notably manifested in the ban on fracking in New York and Vermont. Much of this angst is related to the perception that fracking places groundwater at risk from contamination by the chemicals used as injectants during the fracking process.

In this paper, we discuss the role played by injectants in frac jobs. Using a unique dataset that combines information on the injectants used in frac jobs, together with information on the productivity from these wells and the toxicity of the ingredients, we obtain estimates of the nature of various ingredients in the production function for natural gas extracted from these wells. Our results indicate the largest marginal product of injecting is largest for crosslinkers and breakers as well as a catch-all residual category. We also obtain results related to toxicity, which point to the potential importance of undisclosed ingredients

[21] Our empirical application is not in a shale province, but rather in western tight sands that display some similar geological properties.

employed as gels to increase fluid viscosity on the incidence of toxic additives.

We also find an important correlation between the toxicity of reported injectants and the number of injectants whose identity is withheld under the “trade secrets” provision. In addition, our results suggest a trend towards increasing toxicity over time towards the end of our sample, and further suggest a particular firm-specific role for one operator (Operator I) and one service company (Service Company B). These results take on added significance in light of our finding that Service Company B is the most secretive. In light of the impending acquisition of one of the major service companies by another, this firm-specific information has particular implications for the likelihood of greater withholding going forward.

One policy implication of our analysis is that benefits will accrue from diminishing firms’ ability to withhold information concerning the ingredients used in the frac job. This finding takes on added significance in light of the policy recently proposed by the EPA, which would require more transparency in the reporting of ingredients in frac jobs. Aside form the possibility that this regulation could obviate public fears about fracking, our results suggest the regulation could motivate firms to use less toxic mixes. Whether such a shift would adversely impact productivity is unclear; while our results are not inconsistent with the argument that the potentially toxic ingredients in the “secret sauce” might enhance productivity, they do not suggest such ingredients are indispensable.

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Table 7: Initial Results

	(1) Log 6 Month Gas	(2) Log 6 Month Gas	(3) Log 12 Month Gas	(4) Log 12 Month Gas	(5) Log 6 Month BOE	(6) Log 6 Month BOE	(7) Log 12 Month BOE
Log H_2O Volume	0.12	0.41*	0.19**	0.49**	0.11	0.40*	0.17*
	(0.093)	(0.21)	(0.094)	(0.22)	(0.094)	(0.21)	(0.095)
Sand/Water Ratio	-1.52*	-0.027	-0.33	0.57	-1.63*	-0.088	-0.44
	(0.90)	(0.94)	(0.91)	(0.95)	(0.90)	(0.94)	(0.92)
Log Treated Interval	0.66***	0.29*	0.55***	0.21	0.60***	0.23	0.50***
	(0.088)	(0.17)	(0.079)	(0.16)	(0.091)	(0.17)	(0.082)
Additive		0.0045		0.0094		0.011	
		(0.049)		(0.048)		(0.048)	
Biocide		0.047		-0.064		0.050	
		(0.17)		(0.15)		(0.17)	
Breaker		0.12		0.12		0.11	
		(0.076)		(0.076)		(0.075)	
Gel		0.0058		0.045		0.0067	
		(0.12)		(0.12)		(0.12)	
Slicks		-0.024		-0.015		-0.0061	
		(0.087)		(0.080)		(0.088)	
Unspecified		0.19		0.20		0.19	
		(0.12)		(0.12)		(0.12)	
Constant	5.62***	6.79***	5.96***	6.22**	4.61***	6.02**	4.91***
	(1.63)	(2.59)	(1.63)	(2.46)	(1.67)	(2.62)	(1.67)
N	204	204	204	204	204	204	204
R^2	0.21	0.30	0.17	0.26	0.19	0.28	0.15

Notes: Robust standard errors in parentheses.

Table 8: Various Fixed Effect Results, First Six Months' Gas

	(1) Log 6 Month Gas	(2) Log 6 Month Gas	(3) Log 6 Month Gas	(4) Log 6 Month Gas	(5) Log 6 Month Gas	(6) Log 6 Month Gas
Log H_2O Volume	0.12	0.12	0.20*	0.40***	0.43***	0.46***
	(0.093)	(0.096)	(0.10)	(0.15)	(0.16)	(0.16)
Sand/Water Ratio	-1.52*	-1.44	-0.26	-0.29	0.053	0.048
	(0.90)	(0.87)	(1.04)	(1.01)	(1.13)	(1.05)
Log Treated Interval	0.66***	0.58***	0.54***	0.021	0.0055	0.27
	(0.088)	(0.12)	(0.11)	(0.19)	(0.21)	(0.21)
Stages		0.014	0.0086	0.0038	0.0045	0.0056
		(0.014)	(0.014)	(0.015)	(0.015)	(0.014)
2011			0.13			
			(0.22)			
2012			0.37			
			(0.24)			
2013			0.40			
			(0.26)			
Operator II				0.73***		
				(0.23)		
Service Company B					0.95***	
					(0.30)	
Service Company C					0.22	
					(0.17)	
Constant	5.62***	6.10***	4.99**	6.47***	6.01***	3.89
	(1.63)	(1.91)	(2.02)	(1.71)	(2.19)	(2.47)
N	204	204	204	204	183	204
R^2	0.21	0.22	0.25	0.30	0.31	0.36

Notes: Robust standard errors in parentheses. Operator I is the excluded group: operators III and IV are dropped from the trimmed sample. Column 6 has spatial fixed effects, which are jointly significant.

Table 9: Toxicity Results

	(1) Log 6 Month Gas	(2) Log 6 Month Gas	(3) Log 12 Month Gas	(4) Log 12 Month Gas	(5) Log 6 Month BOE	(6) Log 6 Month BOE	(7) Log 12 Month BOE	(8) Log 12 Month BO
Log Water Volume (gal)	0.41*	0.51**	0.49**	0.64**	0.40*	0.49**	0.47**	0.63**
	(0.21)	(0.25)	(0.22)	(0.25)	(0.21)	(0.25)	(0.23)	(0.25)
Sand/Water Ratio	-0.027	-1.50	0.57	-0.97	-0.088	-1.64	0.50	-1.10
	(0.94)	(1.00)	(0.95)	(0.98)	(0.94)	(1.00)	(0.96)	(0.98)
Log Treated Interval	0.29*	0.19	0.21	0.094	0.23	0.12	0.15	0.032
	(0.17)	(0.19)	(0.16)	(0.15)	(0.17)	(0.20)	(0.16)	(0.15)
Additive	0.0045		0.0094		0.011		0.016	
	(0.049)		(0.048)		(0.048)		(0.048)	
Biocide	0.047		-0.064		0.050		-0.061	
	(0.17)		(0.15)		(0.17)		(0.15)	
Breaker	0.12		0.12		0.11		0.11	
	(0.076)		(0.076)		(0.075)		(0.075)	
Gel	0.0058		0.045		0.0067		0.046	
	(0.12)		(0.12)		(0.12)		(0.12)	
Slicks	-0.024		-0.015		-0.0061		0.0019	
	(0.087)		(0.080)		(0.088)		(0.080)	
Unspecified	0.19		0.20		0.19		0.20	
	(0.12)		(0.12)		(0.12)		(0.12)	
Additive × Toxicity		-0.029**		-0.030**		-0.030**		-0.031**
		(0.013)		(0.013)		(0.013)		(0.013)
Breaker × Toxicity		0.010		0.0067		0.0097		0.0062
		(0.0070)		(0.0069)		(0.0070)		(0.0068)
Gel × Toxicity		-0.0089		-0.0039		-0.0095		-0.0045
		(0.017)		(0.016)		(0.017)		(0.016)
Slicks × Toxicity		0.12**		0.13**		0.12**		0.13**
		(0.052)		(0.052)		(0.052)		(0.052)
Unspecified × Toxicity		-0.073		-0.089		-0.072		-0.089
		(0.055)		(0.055)		(0.055)		(0.055)
Constant	6.79***	4.00	6.22**	3.36	6.02**	3.00	5.39**	2.30
	(2.59)	(3.16)	(2.46)	(3.11)	(2.62)	(3.17)	(2.50)	(3.12)
Observations	204	204	204	204	204	204	204	204
R^2	0.30	0.33	0.26	0.32	0.28	0.31	0.23	0.31

Notes: Robust standard errors in parentheses. Biocide is excluded due to collinearity; see table 3.

Table 10: Trade Secret Results

	(1) Log 6 Month Gas	(2) Log 6 Month Gas	(3) Log 12 Month Gas	(4) Log 12 Month Gas	(5) Log 6 Month BOE	(6) Log 6 Month BOE	(7) Log 12 Month BOE	(8) Log 12 Month BC
Log Water Volume (gal)	0.41*	0.36***	0.49**	0.42***	0.40*	0.35***	0.47**	0.40***
	(0.21)	(0.12)	(0.22)	(0.13)	(0.21)	(0.12)	(0.23)	(0.13)
Sand/Water Ratio	-0.027	-0.86	0.57	-0.043	-0.088	-0.93	0.50	-0.11
	(0.94)	(1.03)	(0.95)	(1.07)	(0.94)	(1.03)	(0.96)	(1.07)
Log Treated Interval	0.29*	0.13	0.21	0.026	0.23	0.062	0.15	-0.034
	(0.17)	(0.17)	(0.16)	(0.13)	(0.17)	(0.17)	(0.16)	(0.13)
Additive	0.0045		0.0094		0.011		0.016	
	(0.049)		(0.048)		(0.048)		(0.048)	
Biocide	0.047		-0.064		0.050		-0.061	
	(0.17)		(0.15)		(0.17)		(0.15)	
Breaker	0.12		0.12		0.11		0.11	
	(0.076)		(0.076)		(0.075)		(0.075)	
Gel	0.0058		0.045		0.0067		0.046	
	(0.12)		(0.12)		(0.12)		(0.12)	
Slicks	-0.024		-0.015		-0.0061		0.0019	
	(0.087)		(0.080)		(0.088)		(0.080)	
Unspecified	0.19		0.20		0.19		0.20	
	(0.12)		(0.12)		(0.12)		(0.12)	
Additive × Secret		0.00024		0.0034		0.00031		0.0035
		(0.014)		(0.011)		(0.014)		(0.011)
Biocide × Secret		-0.011		-0.0048		-0.011		-0.0044
		(0.012)		(0.0092)		(0.012)		(0.0094)
Breaker × Secret		0.0029		-0.0093		0.0024		-0.0097
		(0.012)		(0.0079)		(0.012)		(0.0080)
Gel × Secret		0.013		0.0082		0.014		0.0092
		(0.013)		(0.010)		(0.013)		(0.011)
Slicks × Secret		-0.036		-0.059*		-0.038		-0.061*
		(0.040)		(0.032)		(0.040)		(0.033)
Unspecified × Secret		-0.0054		-0.0047		-0.0054		-0.0047
		(0.0080)		(0.0068)		(0.0080)		(0.0069)
Constant	6.79***	6.34***	6.22**	6.76***	6.02**	5.37***	5.39**	5.75***
	(2.59)	(1.58)	(2.46)	(1.54)	(2.62)	(1.63)	(2.50)	(1.59)
Observations	204	204	204	204	204	204	204	204
R^2	0.30	0.33	0.26	0.31	0.28	0.31	0.23	0.29

Notes: Robust standard errors in parentheses.

Table 11: Panel Results, Log Monthly Gas Production

	(1) log Gas	(2) log Gas	(3) log Gas	(4) log Gas
Well Age	-0.075**	-0.076**	-0.076**	-0.076**
	(0.010)	(0.011)	(0.011)	(0.011)
Log Water Volume (gal)	0.27***	0.50***	0.33***	0.28***
	(0.0083)	(0.011)	(0.020)	(0.021)
Sand/Water Ratio	0.44***	0.52***	-0.24	0.30**
	(0.027)	(0.049)	(0.34)	(0.032)
Log Treated Interval	-0.055**	-0.020	-0.083	-0.0094
	(0.0099)	(0.022)	(0.032)	(0.0069)
Stages	0.038***	0.027***	0.046***	0.040***
	(0.00084)	(0.0024)	(0.0014)	(0.0012)
Additive		0.12**		
		(0.017)		
Breaker		0.11**		
		(0.017)		
Unspecified		0.052***		
		(0.0025)		
Additive × Toxicity			0.0046	
			(0.0044)	
Breaker × Toxicity			-0.0076	
			(0.0035)	
Unspecified × Toxicity			-0.036	
			(0.017)	
Breaker × Secret				-0.0049*
				(0.0015)
Unspecified × Secret				-0.0020
				(0.0016)
Constant	6.97***	5.69***	6.34***	6.44***
	(0.18)	(0.14)	(0.39)	(0.39)
Observations	1868	1664	1664	1664
R^2	0.35	0.37	0.35	0.35

Notes: Operator clustered standard errors in parentheses.

Table 12: Count Model Results

	(1) Poisson	(2) Negative Binomial	(3) OLS
Log Water Volume (gal)	-0.39***	-0.39***	-2.42***
	(0.061)	(0.061)	(0.54)
Sand/Water Ratio	0.82*	0.82*	8.37
	(0.49)	(0.49)	(5.80)
Stages	0.011*	0.011*	0.094**
	(0.0058)	(0.0058)	(0.045)
Secret Gel Count	0.13***	0.13***	0.50*
	(0.044)	(0.044)	(0.30)
Secret Slicks Count	0.15**	0.15**	1.02**
	(0.066)	(0.066)	(0.45)
Secret Unspecified Count	-0.044**	-0.044**	-0.32**
	(0.021)	(0.021)	(0.14)
Operator I	0.94***	0.94***	6.53***
	(0.12)	(0.12)	(1.04)
Operator II	-0.65***	-0.65***	-4.42***
	(0.17)	(0.17)	(1.53)
Service Company A	-1.36***	-1.36***	-10.2***
	(0.13)	(0.13)	(0.98)
Service Company C	-1.51***	-1.51***	-10.8***
	(0.18)	(0.18)	(1.68)
2011	-0.12	-0.12	-0.64
	(0.085)	(0.085)	(0.68)
2012	0.34***	0.34***	1.92***
	(0.096)	(0.096)	(0.73)
2013	0.42***	0.42***	2.37***
	(0.11)	(0.11)	(0.84)
Constant	7.65***	7.65***	43.1***
	(0.90)	(0.90)	(8.70)
Individual Heterogeneity		-17.1***	
		(0.14)	
Observations	294	294	294
Pseudo-R^2	0.18	0.17	
R^2			0.64

Notes: Dependent variable is count of all injected additives that appear on OSHA Occupational Chemical Database as potentially toxic hazards. Point estimates with robust standard errors reported in parentheses.

A Appendix Tables

Table A.1: Characterization of Fluid Additives by Purpose

Category	Additive	Purpose	Examples
Gels	Gels & Foamers	Increase Fluid Viscosity	Guar gum, ethanol, methanol
Slicks	Friction Reducers	Reduce Viscosity	Polyacrimide
	Surfactants	Maintain Viscosity	Sodium lauryl sulfate
Linker & Breaker	Breaker	Reverse Crosslinking	Calcium chloride, sodium chloride, ammonium sulfate
	Crosslinker	Increase Viscosity	Borate salts, ammonium chloride, ethylene glycol
Biocide	Biocide	Kill Bacteria	Quartenary ammonium compounds, glutaraldehyde
Additives	pH Adjuster	Chemical Performance	Acetic acid, potassium hydroxide, sodium hydroxide
	Corrosion Inhibitor	Prevent Corrosion	Acetaldehyde, acetone
	Scale Inhibitor	Protect Piping, Maintain Flow	Phosphonic acid salts, sodium polycarbonate
	Iron Control	Maintain Flow	Citric acid, acetic acid, sodium erythorbate
	Clay Control	Maintain Flow	Choline chloride, potassium chloride, sodium chloride
Unspecified	Non-Specific	Various	

Notes: Categories provided by Stringfellow et al. (2014). Classification of additives was made from cross-references within FracFocus records, Stringfellow et al. (2014), and EPA (2015).

Table A.2: Share of Secret and Toxic Injected Ingredients, by Operator

	Mean	**SD**	**N**
I			
Secret	0.020	0.032	258
Toxic	0.123	0.070	258
II			
Secret	0.211	0.127	226
Toxic	0.168	0.049	226
III			
Secret	0.019	0.005	71
Toxic	0.053	0.018	71
IV			
Secret	0.046	0.021	17
Toxic	0.161	0.048	17
Total			
Secret	0.096	0.124	572
Toxic	0.133	0.068	572

Notes:

Table A.3: Share of Secret and Toxic Injected Ingredients, by Service Company

	Mean	**SD**	**N**
A			
Secret	0.019	0.012	90
Toxic	0.076	0.073	90
B			
Secret	0.199	0.130	245
Toxic	0.168	0.049	245
C			
Secret	0.020	0.033	238
Toxic	0.120	0.063	238
Total			
Secret	0.097	0.125	573
Toxic	0.133	0.068	573

Notes: