ENERGY INSTITUTE AT HAAS

EI @ Haas WP 223R

Corporate Incentives and Nuclear Safety

Catherine Hausman

Revised November 2011

Energy Institute at Haas
2547 Channing Way, # 5180
Berkeley, California 94720-5180
http://ei.haas.berkeley.edu

Corporate Incentives and Nuclear Safety

Catherine Hausman*

November, 2011

Abstract

Approximately half of all commercial U.S. nuclear power reactors have been sold by public utilities to private, independent power producers in the past fifteen years. Previous work has found evidence of dramatically increased generation at these divested plants. At the time of the ownership transfers, some policy makers raised concerns that profit-maximizing corporations would ignore safety. Others, however, claimed that deregulation and consolidation would improve reactor management, and that corporations would work hard to avoid costly plant shutdowns. This paper provides the first comprehensive evidence of the impact of these ownership transfers on plant safety. Using a model of endogenous maintenance decisions, I show conditions under which safety is expected to improve following deregulation. I find empirical evidence that safety did not deteriorate, and in some cases increased, following divestiture.

Key words: nuclear safety, nuclear power, deregulation
JEL: D21, D22, D62, L51, L94

*Ph.D. candidate, Agricultural and Resource Economics, UC Berkeley, and research assistant, Energy Institute at Haas, Haas School of Business. Email: chausman@berkeley.edu. I am grateful to Max Auffhammer, Peter Berck, Severin Borenstein, Lucas Davis, and Catherine Wolfram for their invaluable advice. I thank Meredith Fowlie, Daniel Hausman, Joshua Hausman, Koichiro Ito, Charles Seguin, and Anna Spurlock for excellent comments. This work was supported in part under a research contract from the California Energy Commission to the Energy Institute at Haas. All errors are mine.

1 Introduction

The last decade saw a transformation in the U.S. nuclear power industry. Deregulation led to numerous plant divestitures,[1] ownership of reactors became increasingly consolidated, and generation rose at existing reactors. Operating efficiency, as measured by the ratio of generation to capacity, increased from 75 percent in the 1990s to over 90 percent in the 2000s (Davis and Wolfram 2011). An open question is how deregulation impacted nuclear plant safety. When deregulation began in the late 1990s, some feared that profit-maximizing corporations would ignore safety concerns. Others, however, claimed that deregulation and consolidation would improve reactor management, and that corporations would work hard to avoid costly plant shutdowns. David Lochbaum of the Union of Concerned Scientists was quoted in the New York Times as saying "[t]he new owner of a nuclear power plant clearly has a commitment to a nuclear future... you can also make the counterargument that the new owner is only trying to make a quick buck, to recoup their investment and make some money."[2] More than a decade has passed since divestitures began, and their impact on safety remains unknown. This is the first paper, to my knowledge, to provide comprehensive evidence of this impact, and it has implications for the broader literature on privatization and social welfare. While privatization is generally expected to lower internalized costs, the effect on social costs remains an important open question. This paper contributes to that literature by exploring how the correlation of reliability (the benefits of which are internalized) with safety (the benefits of which are not fully internalized) affects outcomes under privatization.

I begin with a theoretical model of maintenance, an endogenous effort variable, at a profit-maximizing plant. I examine both maintenance for reliability (i.e., no unplanned outages) and for safety. While the costs of the former are generally limited to lost revenues for the plant, the latter can represent risk to the general public. I show that the firm chooses a lower level of maintenance than is socially optimal, leading to socially sub-optimal levels of reliability and safety. However, I also show that when reliability and safety are correlated, the firm invests in safety even when it does not internalize any of the costs of an unsafe event. I then derive implications for a movement from rate-of-return regulation to a deregulated electricity market, showing that reliability and safety measures are expected to improve. Under rate-of-return regulation, utilities generally do not fully internalize the cost of nuclear plant outages; regulators allow the utility to pass on to customers (some or all of) the higher cost associated with running a thermal (coal, natural gas) plant when the nuclear plant

[1] As described below, divestiture can involve either transfer to an unregulated subsidiary of the regulated utility or sale to an independent power producer.

[2] Wald, Matthew L. 2000. "Safety a Worry as Companies Shop for Nuclear Reactors" *New York Times*, February 22.

is out. Divested plants, on the other hand, operate as merchant generators (selling their output in the competitive wholesale market), and their owners lose large operating profits when the plant is offline. Thus, there is a strong incentive to improve reliability following divestiture. Since many of the maintenance actions that improve reliability also improve safety, the model predicts that divested plants will be safer than utility-owned plants.

To test the predictions of my model, I analyze data on five safety measures: initiating events (unplanned power changes), fires, escalated enforcement actions,[3] collective worker radiation exposure, and average worker radiation exposure. My empirical strategy exploits the fact that only half of the reactors in the U.S. reactors were divested and that the timing of divestiture varied widely. These differences in divestiture were largely the outcome of differential electricity deregulation legislation across states. I make the identifying assumption that this is exogenous to nuclear safety, but I examine the possibility of selection bias across states. Overall, I find evidence that safety did not deteriorate, and in some cases improved, following divestiture. This holds across all five safety measures, and it is robust to various specification checks. When allowing for heterogeneity, I find that newer and larger reactors experienced the largest effects. I find limited evidence of intra-firm spillovers, but no effect of consolidation. There is some evidence for learning over time at divested plants. Finally, I consider the possibility that the results shown include the indirect effect, through generation, of divestiture. That is, the direct effect of divestiture on unsafe events is negative, but divestiture also increases generation, thereby increasing the exposure of the plant to an event. As a result, the total estimated effect on safety may be muted. One implication of this result is that while safety did not worsen, and slightly improved, following divestiture, it substantially improved for given levels of generation.

2 Background and Related Literature

2.1 Electricity Deregulation

Deregulation refers to the broad set of reforms proposed for the U.S. electricity sector in the late 1990s; the set of reforms actually implemented and their timeline varied by state. Prior to deregulation (and in states where deregulation did not occur), local monopoly utilities bundled generation, transmission, and distribution services. Local public utilities commissions (PUCs) set the prices the utilities received so the utilities could recover fixed costs plus a fair rate-of-return (for instance, through average-cost pricing). This cost of service

[3] As described in the data section, escalated enforcement occurs when the Nuclear Regulatory Commission imposes notices of violation and/or financial penalties on plants it deems out of compliance with safety regulations.

pricing is the most extreme form regulation took; typically, some incentives for generators to keep costs low were built into the regulatory process. During deregulation, proposed reforms included separating generation, transmission, distribution, and retailing components of the sector and applying various reforms to each of these. Generation was opened to competition (with transmission and distribution still considered natural monopolies), and prices, entry and exit were deregulated. Retail reforms allowed consumers to choose between competing suppliers. Overviews of the economic and political arguments motivating electricity deregulation, the various forms deregulation could take, and the ex-ante concerns about deregulation can be found in Joskow (1997) and White (1996). As of 2010, fifteen states and the District of Columbia had restructured their electricity sector.

Divestiture refers to the process whereby utilities transfer generation assets to unregulated companies. This can refer to either transfer to an unregulated subsidiary of the regulated utility or sale to an independent power producer. In some states, this was required by legislation, to prevent market power following deregulation. For nuclear power reactors, the main component of deregulation expected to affect operations is this entry into competitive wholesale markets.

The main economic argument for generation deregulation was to increase efficiency and lower costs. Efficiency gains with deregulation are generally thought to come from aligning incentives vis-a-vis input choices, as in the Averch and Johnson (1962) model, described below, or from correcting agency problems, as in the Laffont and Tirole (1986) model. For overviews of these models and their extensions, see Baron (1989) and Kahn (1988). There is robust empirical evidence of efficiency gains at power plants in the U.S. following deregulation. Fabrizio, Rose, and Wolfram (2007) find three to five percent efficiency gains at fossil fuel plants following deregulation. The main mechanism they posit is the reduction of information asymmetries, in line with an agency model of managerial effort. Knittel (2002) finds efficiency gains for some types of incentive regulation (in which regulators adjust rates to promote efficiency) at fossil fuel plants. Similarly, Zhang (2007) finds that electricity restructuring (prior to divestiture) improved nuclear operating efficiency. Most recently, Davis and Wolfram (2011) find significant efficiency improvements (10 percentage points) at divested nuclear power plants.

An important assumption in the modeling and empirical sections of this paper is that electricity deregulation was exogenous to nuclear power plant performance. The rationale for this assumption is that divestiture was tied very closely to state-level electricity deregulation, which was driven by a host of political and economic factors. Past nuclear power plant construction certainly was one motivator for deregulation, through the "stranded costs" problem. Since electricity prices were set at average rather than marginal cost, historical nuclear construction (which had large cost over-runs) led to regulated electricity rates that were much higher than wholesale prices. Thus states with high historical nuclear fixed costs may have been more likely to deregulate (Joskow 1997, Griffin and Puller 2005). Davis and Wolfram (2011) find a slightly higher construction cost for plants that were eventually divested, however the difference is small (4 percent) and not statistically significant. Moreover, any difference in past nuclear construction costs should be time-invariant, and as such can be controlled for in empirical specifications with fixed effects. To my knowledge, poor nuclear safety records did not play a role in electricity restructuring.

Note that the impact of divestiture should be interpreted as including two endogenous features. First, it is possible that a utility seeking to sell its nuclear reactor would invest in plant improvements prior to the sale. This is particularly likely at poor performers, which utilities might be afraid they would be unable to sell. Second, while the act of divestiture may be exogenous to plant characteristics and performance, which company buys the plant is not exogenous. That is, there were several companies that purchased divested reactors, and they likely sorted on plant characteristics. Neither feature of deregulation should affect the validity of the empirical estimation in this paper, but they may affect the mechanisms through which the impact of divestiture operates.

2.2 Nuclear Power

There are currently 65 nuclear power plants in the U.S., accounting for 10 percent of total electric capacity. Because nuclear power plants are "baseload," meaning that they run around the clock, they contribute 20 percent of total electricity generation (NRC 2010). Most of the nuclear plants in the U.S. have multiple reactors, and there are currently 104 operating reactors. Of the 65 plants, 29 have one operating reactor, 33 have two, and 3 have 3 reactors each.

Design capacity ranges from 470 to 1304 megawatts.[4] There are two types of reactors in the United States, pressurized-water reactors (PWRs) and boiling-water reactors (BWRs), made by four companies: Babcock & Wilcox Co (B&W), Combustion Engineering, Inc. (CE), General Electric Co. (GE) and Westinghouse Corp. In both types of reactor, fuel assemblies containing enriched uranium create heat, which then produces steam to turn a turbine. One-third of the units in the U.S. are PWRs, and two-thirds are BWRs. When a plant has multiple reactors, those reactors might not be of the same size or manufacturer (although there are no cases of a power plant with both a PWR and a BWR.) For instance,

[4]Here and throughout this paper, capacity refers to megawatts-electrical. Capacity can be measured in MWe (megawatts - electrical) or MWt (megawatts - thermal). The difference between the two arises from the loss of energy through waste heat.

Arkansas Nuclear One has a B&W-manufactured PWR with a design capacity of 850 MWe and a CE-manufactured PWR with a design capacity of 912 MWe. Nine Mile Point has two reactors, both manufactured by GE, but with design capacities of 620 MWe and 1080 MWe.

Nuclear power plants have several advantages relative to fossil fuels plants. Once a nuclear power plant is built, its marginal costs are low.[5] Furthermore, it emits no carbon dioxide. Nuclear power also has advantages over alternative energies such as wind and solar, as it is not intermittent. Also, it can theoretically be built in areas where wind and solar are cost ineffective and hydroelectric resources are unavailable. However, nuclear power has several large disadvantages. Plants are expensive to build, so the levelized cost of nuclear power may be higher than that of fossil fuel plants (Davis 2011). Accidents at nuclear power plants can be catastrophic, and the public has been understandably wary in the wake of the events at Three Mile Island (in 1979), Chernobyl (in 1986), and Fukushima (in 2011). The potential of terrorists or hostile nations acquiring radioactive materials (or attacking U.S. sites) is a concern. Finally, one of the main concerns raised by environmentalists is the treatment, storage, and transport of spent nuclear fuel. The U.S. currently has no national program to deal with nuclear waste; neither does it reuse spent fuel. Spent fuel assemblies are generally stored in pools at power plants, but some plants have reached their capacity for storing spent fuel. Additional storage is available in dry casks at power plants or at separate storage facilities. As of 2009, approximately 60,000 metric tons of spent fuel were stored at power plants (NRC 2010).

Nuclear power plant safety is regulated in the U.S. by the Nuclear Regulatory Commission (NRC), a government agency. The NRC also regulates nuclear research facilities and radioactive waste. It is responsible for licensing and inspections. The NRC has the ability to require unsafe plants to shut down; it can also apply fines for safety violations.

Nuclear reactor liability in the event of an accident is regulated by the Price-Anderson Act (PAA), passed in 1957 and most recently renewed in 2005. The PAA has a three-tiered liability system. Nuclear power operating companies are required to purchase the maximum insurance coverage available in the private market, $375 million annually as of 2010. The second tier is a joint pool; companies are required to pay retrospective premiums in the event of an accident. Companies must prove to the NRC that they will be able to make these payments by, for instance, posting a bond. Retrospective payment is currently set at approximately $112 million per reactor per incident, or $12 billion total per incident (with 104 operating reactors). The federal government is responsible for all payments above

[5] According to the EIA's Electric Power Annual (EIA 2011), variable costs (including operating, maintenance, and fuel) were 2.169 cents per kilowatt-hour for nuclear plants and 4.048 for fossil-steam plants. For nuclear plants, operating and maintenance costs represent the majority of variable costs; for fossil-steam plants, fuel costs are the largest portion.

this primary and secondary coverage. The Price-Anderson Act covers liability claims but not on-site damages; the NRC separately requires companies to maintain funds for these damages.

While some work has been done on nuclear power plant safety (Feinstein 1989, Hanemann et al. 1992, Rothwell 1989), very little has focused directly on the issues related to profitability and deregulation. Verma, Mitnick and Marcus (1999) look at incentive regulation programs (prior to divestiture), finding mixed and statistically insignificant results for power plant safety. Bier et al. (2001) expect the effect of deregulation on nuclear power plant safety to be ambiguous, based on economic theory and the experience of other deregulated industries (airlines, railroads, and the U.K. electricity sector). Rust and Rothwell (1995) examine forced outages before and after the Three Mile Island accident, finding that safety comes at the expense of profitability because of increased maintenance costs. David, Maude-Griffin, and Rothwell (1996) also examine unplanned outages following the Three Mile Island accident. However, the plants evaluated in both papers are all in regulated electricity markets.

A related strand of literature examines the effect of deregulation on safety records in other industries, such as airlines and railroads. Here the evidence has been mixed: Barnett and Higgins (1989) find negative effects for the safety records of new entrant airlines allowed by deregulation. Kennet (1993) finds that while deregulation led to more infrequent aircraft engine maintenance, engine reliability did not suffer, and may have improved. In related work, Golbe (1986) finds a weak negative relationship between airline safety and profitability, whereas Rose (1990) finds that airline safety is positively correlated with profitability. Importantly, though, one of the main mechanisms through which safety and profitability are related in air travel is in the consumer's demand function; this mechanism is not expected to operate in the case of nuclear power generation, as electricity is not differentiable for end-users. Galiani et al. (2005) show that water privatization in Argentina led to improved water quality and lower child mortality, providing evidence that privatization can positively impact social welfare in ways beyond cost reduction.

3 Model

I start with a model for profit maximization of a divested nuclear power plant. I derive implications for expenditures on reliability and safety maintenance. I then explore how the incentives would change under rate-of-return regulation.

3.1 Profit-Maximization with Reliability

Consider a baseload nuclear power plant in a deregulated electricity generation market. For simplification, assume the power plant has only one reactor. The power plant faces a given price per megawatt-hour (MWh) p and given fuel and other variable costs per MWh, c^o. The market price of electricity generation is determined by the marginal cost of the marginal plant. Variable costs for nuclear plants are lower than for fossil fuel plants, implying that nuclear plants are not the marginal plants. According to a recent EIA report (EIA 2009), variable costs are 2.17 cents per kilowatt-hour for nuclear plants and 4.05 for fossil-steam plants. First, assume that the nuclear plant is a price-taker.[6] Second, assume that $p > c^o$; the market price is higher than the nuclear plant's variable costs.[7]

If the plant is operating, it operates at capacity, i.e., producing quantity q of electricity. Let operating (not total) profits $\pi = pq - c^o q$. Assume there are no ramping or start-up costs. The plant can choose some level of maintenance a to purchase; thus a is an endogenous effort variable. Increases in a can be thought of as increases in either the quantity or quality of effort. Most maintenance for nuclear power plants requires the plant to be offline, so maintenance incurs both direct costs and lost operating profits. The cost of maintenance is $c(a, \pi)$, where $c(a, \pi) \geq 0$, $\frac{\partial c}{\partial a} > 0$, $\frac{\partial c}{\partial \pi} > 0$, $\frac{\partial^2 c}{\partial^2 a} > 0$ and $\frac{\partial^2 c}{\partial a \partial \pi} > 0$. The intuition for the assumptions on the first and second derivatives with respect to operating profits π is that additional maintenance requires a longer time offline, so more revenue is lost.[8] In any given period, there is a probability $r(a) \in (0, 1)$ that the plant will experience an unplanned outage (or "scram" or "trip"), conditional on the plant deciding ex-ante to operate. Then the probability of being able to operate as planned is given by $1 - r(a)$. Assume $r'(a) < 0$: maintenance (effort) decreases the probability of an unplanned outage. Also, $r''(a) > 0$: the probability decreases at a decreasing rate. Intuitively, the probability asymptotes as maintenance increases. In the event of an unplanned outage, the firm earns no revenue (as it produces no electricity) and incurs additional costs $c^u > 0$. These additional costs may include repair work, increased (safety) regulatory scrutiny, or bad publicity. The firm's profit

[6] There is potential for the owner of a nuclear power plant to exercise market power, if it owns other generators. However, if the other generators have higher marginal costs than the nuclear plant, exercising market power by shutting down the nuclear plant is not the first-best strategy of the firm. Rather, the firm would take the higher cost plant offline. Moreover, if the nuclear power plant is baseload, the owner may be required to purchase replacement power when the plant is down. Since the replacement power is more costly than the nuclear plant's generation, the firm has no incentive to exercise market power by taking the nuclear plant offline.

[7] For representative supply and demand curves showing nuclear marginal costs compared to fossil fuel costs, see Griffin and Puller (2005).

[8] It is straightforward to consider the case where $\frac{\partial c}{\partial \pi} = 0$, i.e., maintenance does not require the plant to be offline.

maximization problem is[9]

$$\max_{a} \quad (1 - r(a)) \cdot \pi - r(a) \cdot c^u - c(a, \pi) \tag{1}$$

The first-order condition is

$$-r'(a) \cdot \pi - r'(a) \cdot c^u - \frac{\partial c(a, \pi)}{\partial a} = 0 \tag{2}$$

The firm chooses the level of maintenance a such that the marginal benefit of an additional unit of maintenance $-r'(a) \cdot \pi - r'(a) \cdot c^u$ equals the marginal cost $\frac{\partial c(a,\pi)}{\partial a}$. The marginal benefit of an additional unit of maintenance is an increased likelihood of earning revenue and a decreased likelihood of paying for an unplanned outage. Comparative statics on the exogenous revenue and cost variables is straightforward. By the implicit function theorem,

$$\begin{bmatrix} \frac{\partial a}{\partial \pi} \\ \frac{\partial a}{\partial c^u} \end{bmatrix} = - \left[-r''(a) \cdot \pi - r''(a) \cdot c^u - \frac{\partial^2 c(a, \pi)}{\partial^2 a} \right]^{-1} \cdot \begin{bmatrix} -r'(a) - \frac{\partial^2 c}{\partial a \partial \pi} \\ -r'(a) \end{bmatrix} \tag{3}$$

At the profit maximizing level of a, $\left[-r''(a) \cdot \pi - r''(a) \cdot c^u - \frac{\partial^2 c(a,\pi)}{\partial^2 a} \right]$ is negative (by the second order condition, which is satisfied according to the above assumptions),[10] and recall that $r'(a)$ is assumed to be negative and $\frac{\partial^2 c(a,\pi)}{\partial^2 a}$ positive. The sign on $\frac{\partial a}{\partial \pi}$ is indeterminate; both planned maintenance outages and unplanned outages lead the firm to lose revenue. If one instead assumes that maintenance does not require the plant to be offline, i.e., $\frac{\partial c}{\partial \pi} = 0$, then maintenance a is increasing in potential revenue. (Note that all results on $\frac{\partial a}{\partial \pi}$ imply the same result on $\frac{\partial a}{\partial p}$, since $\frac{\partial \pi}{\partial p} = 1$.) The sign on $\frac{\partial a}{\partial c^u}$ is positive; maintenance is increasing in the cost of an unplanned outage.

---

[9] As an alternative way to see how maintenance costs depend on operating profits, re-write the firm's total profits as $(1 - r(a) - p(a)) \cdot \pi - r(a) \cdot c^u - c(a)$, where $r(a) \in (0, 1)$ is the probability of an unplanned outage, and $p(a) \in (0, 1)$ is the fraction of time spent on planned outages. Thus all time is spent on either planned outages, unplanned outages, or generation. As before, $r'(a) < 0$, $c'(a) > 0$, and now $p'(a) > 0$: the time spent on a planned outage is increasing in the amount of maintenance done. Rearranging the firm's total profit function gives $(1 - r(a)) \cdot \pi - r(a) \cdot c^u - p(a) \cdot \pi - c(a)$. Let $\widetilde{c}(a, \pi) = p(a) \cdot \pi + c(a)$, so that profits equal $(1 - r(a)) \cdot \pi - r(a) \cdot c^u - \widetilde{c}(a, \pi)$. The latter expression is the same as equation 1, showing how the cost of maintenance depends on operating profits.

[10] The key assumption for satisfying the second order condition is that $r''(a) > 0$. Intuitively, this is satisfied for large a if the probability of an unplanned outage asymptotes towards zero as maintenance increases. If $r(a)$ is S-shaped, with $r''(a) < 0$ for small values of a, there could be a corner solution with no maintenance. All that is necessary to rule out this case is to assume that the optimal a is beyond the inflection point; alternatively, one could assume that the regulatory body governing safety (the NRC) requires a minimum level of maintenance.

3.2 Profit-Maximization with Reliability and Safety

The above model considers plant reliability rather than safety. Suppose that the probability of an unsafe event is $s(a) \in (0,1)$ with $s'(a) < 0$ and $s''(a) > 0$; that is, the same maintenance actions that improve reliability also improve safety. Suppose the total cost of an unsafe event is $c^s > 0$, of which some fraction θ are borne by the plant, and the remaining fraction $(1-\theta)$ are borne by society.[11]

The firm's optimum is

$$\max_{a} \quad (1 - r(a)) \cdot \pi - r(a) \cdot c^u - c(a, \pi) - s(a) \cdot \theta \cdot c^s \tag{4}$$

The social optimum is similar but with $\theta = 1$ (society internalizes all of the safety costs).

The firm's first-order condition is

$$-r'(a) \cdot \pi - r'(a) \cdot c^u - \frac{\partial c(a, \pi)}{\partial a} - s'(a) \cdot \theta \cdot c^s = 0 \tag{5}$$

The firm, which does not bear the entire safety cost c^s, exerts less effort a than is socially optimal. However, note that even if the firm internalizes none of the safety costs (i.e., $\theta = 0$), the firm invests in maintenance (because of the reliability costs) that has a positive impact on safety. The social optimum can be achieved if a regulatory agency requires the firm to conduct the optimal level of maintenance. In practice, this may be difficult if the regulatory agency does not have complete information on the cost function $c(a, \pi)$ or the reliability and safety functions $r(a)$ and $s(a)$.

Comparative statics are again straightforward. By the implicit function theorem,

$$\begin{bmatrix} \frac{\partial a}{\partial \pi} \\ \frac{\partial a}{\partial c^u} \\ \frac{\partial a}{\partial \theta} \end{bmatrix} = - \left[-r''(a) \cdot \pi - r''(a) \cdot c^u - \frac{\partial^2 c(a, \pi)}{\partial^2 a} - s'(a) \cdot \theta \cdot c^s \right]^{-1} \cdot \begin{bmatrix} -r'(a) - \frac{\partial^2 c}{\partial a \partial \pi} \\ -r'(a) \\ -s'(a) \cdot c^s \end{bmatrix} \tag{6}$$

As before, at the profit maximizing level of a, $\left[-r''(a) \cdot \pi - r''(a) \cdot c^u - \frac{\partial^2 c(a,\pi)}{\partial^2 a} - s'(a) \cdot \theta \cdot c^s \right]$ is negative (by the second order condition, which is satisfied according to the above assumptions).[12] The sign on $\frac{\partial a}{\partial \pi}$ is again indeterminate, and $\frac{\partial a}{\partial c^u}$ is again positive. Since $s'(a) < 0$, $\frac{\partial a}{\partial \theta} > 0$; effort is increasing in the portion θ of the safety cost that the firm internalizes.

At the other extreme, safety could be unrelated to reliability, in that the maintenance effort that lowers the probability of an unplanned outage is separate from any maintenance

[11] See above for a summary of nuclear reactor liability in the U.S. under the Price-Anderson Act (PAA).

[12] As before, the key assumptions for satisfying the second order condition are that $r''(a) > 0$ and $s''(a) > 0$.

that improves safety. Denote the maintenance that improves reliability as a^r and the maintenance that improves safety as a^s. Both require expenditures by the plant: $c^r(a^r, \pi)$ and $c^s(a^s, \pi)$, with $c(.) > 0$, $\frac{\partial c(.)}{\partial a} > 0$, and $\frac{\partial^2 c}{\partial a \partial \pi} > 0$ (beyond these assumptions, I make no assumptions on the functional form of $c^r(a^r, \pi)$ as compared to $c^s(a^s, \pi)$). As before, additional maintenance requires a longer time offline, so more revenue is lost (the case where reliability and safety maintenance do not require being offline can also be considered, with $\frac{\partial^2 c}{\partial a \partial \pi} = 0$). The firm's problem is

$$\max_{a^r, a^s} \quad (1 - r(a^r)) \cdot \pi - r(a^r) \cdot c^u - c^r(a^r, \pi) - s(a^s) \cdot \theta \cdot c^s - c^s(a^s, \pi) \tag{7}$$

The social optimum is similar but with $\theta = 1$ (society internalizes all of the safety costs).

The firm's first-order conditions are

$$-r'(a^r) \cdot \pi - r'(a^r) \cdot c^u - \frac{\partial c^r(a^r, \pi)}{\partial a^r} = 0 \tag{8}$$

$$-s'(a^s) \cdot \theta \cdot c^s - \frac{\partial c^s(a^s, \pi)}{\partial a^s} = 0 \tag{9}$$

The firm, like the social planner, equates the marginal cost and benefit of reliability maintenance, so that the firm's choice of a^r is equivalent to the social optimum. However, the firm internalizes only a fraction θ of the benefits associated with improved safety, and exerts a sub-optimal level of effort on safety maintenance. (With perfect information and regulatory oversight, the social optimum could again be achieved through regulation of maintenance levels.) The second order conditions are again satisfied.[13] Comparative statics, given in Appendix 1, show that $\frac{\partial a^r}{\partial \pi}$ again has an indeterminate sign, $\frac{\partial a^r}{\partial c^u}$ is again positive, and $\frac{\partial a^s}{\partial \theta}$ is again positive. As expected, $\frac{\partial a^r}{\partial \theta}$ and $\frac{\partial a^s}{\partial c^u}$ are both zero: reliability maintenance does not depend on the costs of safety events and vice-versa. Note that $\frac{\partial a^s}{\partial \pi}$ is negative: potential operating profits unambiguously lower the optimal expenditures on safety maintenance. This follows from the assumption that safety maintenance requires that the plant be offline; if we instead assume $\frac{\partial^2 c(a^s, \pi)}{\partial a^s \partial \pi} = 0$, then potential operating profits will not affect the optimal expenditures on safety maintenance.

3.3 Price-Regulated Plants

Under electricity regulation in the U.S., prices are set by local public utilities commissions (PUCs) so that monopoly utilities recover their costs. Accordingly, variable costs are passed on to rate payers, and utilities are additionally allowed a fair rate-of-return on their fixed

[13] Appendix 1 gives the Hessian matrix, which is negative definite.

costs. Consider a nuclear power plant owned by a local monopolistic utility, which provides electricity generation, transmission, and retail services to its customers. Assume that the local utilities commission sets price equal to the average price of electricity so that the utility recovers its variable and fixed costs.

If the regulatory compact is that the utilities commission will allow the utility to pass on all costs to consumers, then the regulated plant has no incentive to minimize costs. If the nuclear power plant is not generating, the utility will substitute with a more expensive plant (for instance, natural gas-fired), and then pass on this higher generation cost to its customers. In the model above, this would imply that the regulated nuclear power plant faces lower costs of unplanned outages, and the effect on maintenance is unambiguous. From equations (3) and (6), we have $\frac{\partial a}{\partial c^u} > 0$; if the regulated plant faces lower costs of unplanned outages, it will have a lower level of maintenance than would an unregulated plant.

A related effect may be seen for the cost function for maintenance $c(a, \pi)$. In the short term, since the regulated plant can pass on all maintenance costs, maintenance might be higher than under deregulation. In the long run, however, the regulated plant has no incentive to improve technical efficiency. The deregulated plant, in contrast, has an incentive to invest in research and development to lower $c(a, \pi)$ in the long run.

Previous evidence on power plant reliability (Davis and Wolfram 2011) supports these cost effects; the authors find that reactors are available to generate for a significantly higher percentage of the time following divestiture. This improved efficiency appears to have come in the form of shorter refueling outages, enabled by changes in management practices.[14] One newspaper article describes Entergy (one of the larger owners of divested plants) flying a specialist and his equipment on the company jet from one reactor to another to fix an electrical generator.[15]

The previous intuition was for reliability maintenance. Where safety and reliability are perfectly correlated, the effect of deregulation is the same. If maintenance increases, safety will also increase (because both $r(a)$ and $s(a)$ are increasing in a). Even though the firm does not internalize the cost of a safety event, it internalizes the effect of maintenance on reliability. In the case where safety and reliability are uncorrelated, reliability maintenance will increase,

[14] For instance, one article described how "America's deregulation of wholesale power markets put a painful squeeze on the country's dozens of nuclear plants, many of which were run as one-shot investments by incompetent local utilities. That is rapidly changing thanks to a flurry of mergers and joint ventures that is consolidating the industry into the hands of serious managers. Plants benefit from economies of scale in fuel purchases, maintenance crews and sharing of best practice. Big operators like Exelon and Entergy are upgrading steam generators and turbines to squeeze out more juice." Source: Vaitheeswaran, Vijay. 2004. "A Nuclear Renaissance?" *Wall Street Journal*, March 30.

[15] Source: Wald, Matthew L. 2001. "Despite Fear, Deregulation Leaves Nuclear Reactors Working Harder, Longer and Safer." *New York Times*, February 18.

but the effect of deregulation on safety depends largely on whether the deregulated firm internalizes more or less of the cost c^s of a safety event.

Finally, it should be noted that pure cost of service regulation (in which all costs are passed on to consumers) should be viewed as an illustrative case; in practice regulation usually involves some incentives for generators. However, even where utilities were not allowed to pass on all replacement power costs, they could pass on more than could an independent power producer in a deregulated environment.[16] As the president of Entergy said in 2001, "[w]hen you've got hundreds of millions invested – and no regulators or fuel-adjustor clauses, just the competitive marketplace – you must make all your decisions toward the middle of the road and away from the shoulders... As a prudent business matter, you simply cannot risk a long shutdown costing a million dollars a day in lost revenue while all your expenses go on."[17]

3.4 Additional Considerations Under Price Regulation

Two additional models could be applied under price regulation: (1) the Averch-Johnson (1962) effect, in which firms over-invest in capital, and (2) agency models, such as Laffont and Tirole (1986), in which firms exert sub-optimal levels of effort. Averch and Johnson show that plants under rate-of-return regulation over-invest in capital relative to labor. The intuition is simple; under rate-of-return regulation, a firm's profits are a function of its capital investments, since the regulator allows some fair rate-of-return on investment. The Averch-Johnson effect may explain the construction of nuclear power plants, but it is likely not relevant in the operations of nuclear plants. A long history of cost overruns in nuclear power plant construction meant that many local regulators were wary of approving further capital expenditures (Joskow and Schmalensee 1986).

Fabrizio et al. (2007) cite agency models in explaining why deregulation may improve operating efficiency at thermal power plants. In agency models such as Laffont and Tirole (1986), efforts to run a firm efficiently by reducing costs provides some disutility to the firm's

[16] For instance, a 1984 New York Times article about plant reliability stated "[e]very time a nuclear plant is shut down for maintenance or repairs, it costs ratepayers money. A utility must use coal or oil to generate the replacement power, and on a hot day in New York, it can cost more than $500,000 for the substitute power when a reactor is shut for 24 hours" (Wald, Matthew L. 1984. "Nuclear Running Costs Take a Big Bite." *New York Times*, September 16). Similarly, a 1996 New York Times article cited one consultant to utility regulators as saying "[t]he old regime was a regulatory compact... The utility would provide safe and adequate service at reasonable cost, and on the other side, would get a return that was commensurate with that operation," implying "that a company with higher costs simply built that into the rate structure" (Johnson, Kirk. 1996. "For Nuclear Power Plant, Bottom Line Is Death Knell." *New York Times*, October 11).

[17] Source: Cheddar, Christina. 2001. "What Now? - Back in Power: Nuclear Reactors Were Once the Future; They May Be Again." *Wall Street Journal*, September 17.

manager. The regulator fails to compensate the manager for this disutility (perhaps because effort is unobservable or unverifiable), so the manager exerts less effort than is socially optimal. For nuclear plants, efforts to maintain reliability and safety may be particularly unobservable to public utilities commissions, since outages and accidents are stochastic. A manager could, then, exert minimal effort while blaming outages and accidents on bad luck. In the case of nuclear plants, however, this is likely mitigated by an aversion (on the part of both the manager and the public utilities commission) to the public scrutiny that follows extended outages or severe accidents. In that case, managers would be more willing to exert effort to maintain safety and reliability, and regulators would be less willing to treat outages and accidents as bad luck. An argument similar to that made by Laffont and Tirole is made by Kahn (1988); he points out that utilities that are lax about cost reductions and other efficiency gains may not engage in cross-firm cooperation. Anecdotal evidence suggests that cross-firm knowledge sharing increased following deregulation.

4 Empirical evidence

4.1 Data

The Nuclear Regulatory Commission (NRC) tracks a number of safety measures for all reactors in the United States. Reactor operators are required, under title 10 of the Code of Federal Regulations, to provide reports to the NRC following any shutdown, deviation from technical specifications, or event resulting in degraded plant safety. These licensee event reports contain information by date and by plant on the specific event or condition involved, including narrative descriptions, and are publicly available from the NRC. Additionally, the NRC performs regular plant inspections. These can involve inspectors permanently stationed at the plant, regional inspectors, and inspectors for specific areas (for instance, health physics or security). Inspections may involve reviewing records, observing drills and simulations, observing maintenance procedures, and testing equipment. Results are made public by the NRC.

The NRC additionally synthesizes and publishes data on safety measures of particular interest:

- initiating events, including unplanned outages and power changes
- fires
- worker radiation exposure

- escalated enforcement actions, including orders and fines

Data are available since 1988 on initiating events, which could potentially challenge a plant's safety systems, in the report "Rates of Initiating Events at U.S. Nuclear Power Plants 1988–2010." All scrams (or trips), which are unplanned outages, are categorized as initiating events. Unplanned power changes that are not scrams are also categorized as initiating events. Each initiating event is assigned to one of 16 categories, such as "stuck open safety relief valve" or "loss of feedwater." The advantage of analyzing initiating events is that "[i]n general, these risk-significant initiating event categories cover approximately 90% of the internal event core damage risk (excluding internal flooding) from the 103 operating commercial nuclear power plants in the U.S." (Eide, Rasmuson, and Atwood 2005). Since initiating events correspond to unplanned loss of power (either total loss of power, as in a scram, or partial loss of power), these are events in which reliability maintenance overlaps with safety maintenance. As such, the prediction in the modeling section is that the profit-maximizing plant will invest in preventing these, but invest less than is socially optimal. The theoretical model also predicts that the number of these events will decrease following divestiture.

I also analyze fires, a safety event of particular interest to the NRC, for which I have data since 1990. The NRC dataset, "Fire Events Data from Licensee Event Reports," gives the original source document citation, the event date, the plant's mode at the time of the fire (e.g., power operating, refueling), operating capacity on the date of the fire, the physical area involved, (e.g., turbine building versus auxiliary building), and whether an alert was declared (either because more than 15 minutes were required to extinguish the fire, or because the fire affected the safety systems need for plant shutdown). Following a fire at the Browns Ferry plant in 1975,[18] the NRC revised fire regulations. The NRC now performs fire inspections on a regular basis and analyzes fire events for national trends. However, as recently as 2008, the Government Accountability Office (GAO) released a report calling for stricter regulations. The consequences of a fire depend on both where the fire starts (for instance, whether it is close to the reactor building), and on how rapidly the fire can be extinguished. According to the GAO (2008) report, "[t]he most commonly reported cause of fires was electrical followed by maintenance-related causes and the ignition of oil-based lubricants or coolant. Although 13 fires [of the more than 100 fires between 1995 and 2007] were classified as significant alerts, and some of these fires damaged or destroyed unit equipment, NRC officials stated that none of these fires degraded units' safe shutdown capabilities or resulted in damage to nuclear units' core or containment buildings" (p 4). The report concluded that the NRC still

[18]This fire was caused by a worker checking for air leaks with a lit candle. The fire caused extensive damage, including to emergency core cooling systems.

needs to resolve several long-standing issues.

Additionally, I observe annual radiation exposure to individuals at the plant since 1974, using data from the NRC's "Occupational Radiation Exposure at Commercial Nuclear Power Reactors and Other Facilities (NUREG-0713)." Reactors are required to report the radiation exposure of each monitored worker to the NRC, which reviews radiation control and monitoring during its regular plant inspections.[19] Monitoring procedures vary over time, but details of the regulation are given by part 20, "Standards for Protection against Radiation," of title 10 of the CFR, which describes the "as low as (is) reasonably achievable" guidelines for radiation doses. Since the number of individuals could systematically vary across time (for instance, if divested plants employ fewer people), I analyze two separate measures. The first is collective worker radiation exposure, which sums exposure across all people; the second is average worker radiation exposure, which normalizes by the number of individuals monitored.

A final measure of interest for safety is on "escalated enforcement," and is available in the form of NRC dataset "Escalated Enforcement Actions Issued to Reactor Licensees." This tracks, since 1996, the notices of violation and penalties the NRC has imposed on reactors,[20] ranked according to severity level. It is part of the NRC's enforcement program, which focuses on compliance with regulatory requirements and identification and correction of violations. Three sanctions are possible: notices of violation (NOVs), civil penalties (i.e., monetary fines), and orders (e.g., to suspend operations). Minor violations are documented, but the lowest level of violations are not part of the "escalated enforcement" program.[21] For each case, the NRC publicly posts the violation type (NOV and/or order) and severity, the amount of any civil penalty, the date issued, and a short description. This measure tends to lead to public scrutiny; the NRC may call a public meeting or issue a press release, and the violations are often reported by the media.[22]

Generation data are from the U.S. Department of Energy, Energy Information Administration (EIA) Power Plant Report (EIA-923). This survey (previously published as the EIA-906 and EIA-759 reports) provides monthly net generation in megawatt-hours for each nuclear reactor. Following, Davis and Wolfram (2011), I include only reactors operating as of

[19]For instance, a 2003 inspection report for Beaver Valley described NRC review of personnel dosimeters; frisking instruments; radiation portal monitors; protective clothing and self-contained breathing apparatus; radiological work permits; and daily health physics status meetings.

[20]For plants with multiple reactors, notices of violation and penalties may refer to only one reactor, but more commonly refer to all the reactors at the plant. Clustering standard errors at the plant level will account for this cross-reactor correlation.

[21]Additional information on the enforcement process is available in the NRC Enforcement Manual on the NRC website.

[22]See, e.g., Whitaker, Barbara. 2007. "Indian Point Guard Slept on Job, N.R.C. Says." *New York Times*, September 2.

January 1, 2000; this excludes a few reactors that were closed during the 1980s and 1990s.[23] To calculate capacity factor, I normalize generation by reactor design capacity, following Davis and Wolfram. Reactor design capacity is from the EIA "Nuclear Power Generation and Fuel Cycle Report 1997, Appendix C: Nuclear Units Ordered in the United States, 1953-1996." Divestiture dates are from Davis and Wolfram (2011); they compile the dates from the EIA and cross-check them against SEC filings.

Table 1 gives summary statistics on the five safety measures of interest plus generation and capacity factor for all 103 power reactors in operation from 1996 to 2009.[24] The average reactor has slightly fewer than one initiating event per year. Fires are quite rare. Worker radiation exposure averages 117 person-REMs per year. In 2008, this corresponded to roughly 1,000 workers per facility with an average dose of 0.1 rem and a maximum dose of 0.2 rem; for comparison, the average person in the U.S. receives 0.3 rem from background sources of radiation and 0.3 rem from man-made sources (NCRP 2009). The average unit has one escalated enforcement intervention every two years, while producing over 7 million MWh of electricity. The average capacity factor was 88 percent. Note that capacity factors can be negative (since generation measured is net, rather than gross) or greater than 100 percent (because of uprates that allow the unit to produce more generation than the initial design allowed).

To examine the potential for selection bias, table 2 shows mean values for each variable by the reactors' eventual divestiture status. Data are from 1996-1998; 1996 is the first year for which all safety measures are available, and 1998 is the last year in which no plants are divested. Panel A shows that the safety measures are not statistically different at the 5 percent level between the plants that later divest and those that do not. Panel B shows that reliability measures are statistically different at the 1 percent level; plants that were later divested have substantially lower generation and capacity factor. As Davis and Wolfram discuss, reactors that were later divested had much lower generation in the late 1990s, which is explained by several long outages at a few plants. Davis and Wolfram also examine differences in observable fixed reactor characteristics. They find differences in the proportion of boiling water reactors (BWRs) versus pressurized water reactors (PWRs) and differences in the location of the divested facilities. The latter is not surprising, given the regional differences in deregulation patterns. To address concerns on selection bias, I later examine the robustness of the main results to excluding certain states and regions.

[23] Most of these reactors were small and experimental. Exceptions include Browns Ferry 1, Millstone 1, and San Onofre 1.

[24] There are currently 104 reactors in operation. For the empirical section of this paper, I drop Browns Ferry 1. This reactor was shut down from 1985 to 2007, and re-opened only following substantial investment.

4.2 Graphical Analysis

First, I show graphical evidence of the effect of divestiture on each safety measure at the quarterly level. I regress each measure on quarter of sample effects and reactor fixed effects ($event_{i,t} = u_i + v_t + \varepsilon_{i,t}$), then re-normalize the dates in event time (i.e., centering the time scale at each reactor's quarter of divestiture). I then plot the average residual $\varepsilon_{i,t}$ for the divested units. Figure 1 shows this for the sum of the three count variables: initiating events, fires, and escalated enforcement. There is a decrease in incidents following divestiture, although it is smaller than the quarterly noise. The effect is not immediate, implying that there may be an adjustment period following divestiture, or there may be learning over time at divested units. The variance in the measure appears to decrease following divestiture; this is likely a direct implication of the count nature of the data. For a Poisson process, for instance, which equates the mean and variance, any reduction in the mean will also imply a reduction in the variance.

Figures 2-4 show the residuals for each individual type of event. The time period in each figure varies, depending on data availability for each measure. For initiating events (figure 2), there is again an effect following divestiture, but it is not immediate and it is smaller than the quarterly noise. For fires (figure 3), no effect is visually apparent. For escalated enforcement (figure 4), there is a delayed effect following divestiture, which is again smaller than the quarterly noise.

Figure 5 shows the residual for capacity factor, the variable analyzed by Davis and Wolfram (2011). For this variable, a pronounced increase appears at divestiture. Figure 6 shows the two annual worker radiation exposure measures (collective and average), for which no effect of divestiture is apparent.

Overall, the graphical evidence indicates that divestiture had a small negative effect on the quarterly count of two safety incidents: initiating events and escalated enforcement. For both events, the effect is delayed and may have a downward trend, indicating either slow adjustment, learning over time, or both. The effect of divestiture is small relative to the noise in each measure. However, noise decreases in the post-divestiture period. For fires and worker radiation exposure, no effect appears in the graphical evidence. For capacity factors, the graphical evidence shows a pronounced effect, as found by Davis and Wolfram.

4.3 Regression Analysis

I next provide formal tests of the effect of divestiture on safety. Since initiating events, fires, and escalated enforcement are count variables with a large number of zero observations, OLS is not expected to perform well. Accordingly, I begin with a standard count specification, the Poisson regression with fixed effects. The probability of a given number of events $y_{i,t}$ occurring in a month is

$$\Pr(y_{i,t}|\mathbf{x_{it}}) = \frac{\exp\{-\exp(\mathbf{x_{it}B})\}\{\exp(\mathbf{x_{it}B})\}^{y_{it}}}{y_{it}!} \tag{10}$$

with $\mathbf{x_{it}B} = \beta \cdot divest_{i,t} + \alpha_i + v_t + \varepsilon_{i,t}$ and $y_{it} = 0, 1, 2...$ Here, $divest_{i,t}$ is a divestiture dummy, α_i is a reactor fixed effect, and v_t is a set of month and year effects. This model can be estimated by conditional maximum likelihood, in which the α_i coefficients drop out of the estimation. Standard errors are bootstrapped (with 500 repetitions) and clustered by plant/year to account for correlation across reactors in a plant and across months. The fixed effects α_i are an important feature of this model; in addition to flexibly controlling for unobserved characteristics, they help alleviate the over-dispersion problem in Poisson models. The Poisson process assumes equality of the mean and variance, whereas in empirical settings the variance is often larger than the mean (particularly where there are many zero observations). This over-dispersion leads to incorrect inference, with the null hypothesis rejected when it should not be. Fixed effects partially alleviate the problem by requiring only that the mean and variance be equal *within* groups, thus allowing for greater heterogeneity.

For specifications using radiation exposure, OLS regressions are used (since radiation exposure is a continuous variable). These data are collected annually by plant, so I include year effects and facility effects

$$event_{i,t} = \beta \cdot divest_{i,t} + \alpha_i + v_t + \varepsilon_{i,t} \tag{11}$$

Results are given in table 3. To compare the magnitude in the OLS specifications with the magnitude in the count specifications, I have shown the percentage change in the expected number of counts attributable to divestiture for both regressions.[25] For four of the safety measures, the coefficient on divestiture is negative. For initiating events, the coefficient is -0.17; for fires, the coefficient is -0.68; and for escalated enforcement, the coefficient is -0.38. While statistical significance of 5 percent is not achieved for any variable, the magnitude of the coefficient is economically significant for all three. For initiating events, for instance, divestiture leads to a 15 percent reduction in the expected monthly event count. For fires, the percentage change is -0.49, and for escalated enforcement the percentage change is -0.39. Furthermore, moderate positive effects can be ruled out at the 5 percent level. For initiating

[25] The percentage change in the expected number of counts is defined as $\frac{E[y_{it}|d_{it}=1;\alpha_i,v_t]-E[y_{it}|d_{it}=0;\alpha_i,v_t]}{E[y_{it}|d_{it}=0;\alpha_i,v_t]}$. For the count specifications, $E[y_{it}|d_{it};\alpha_i,v_t] = \exp(\beta \cdot divest_{i,t}+\alpha_i+v_t)$. Accordingly, the percentage change in the expected number of counts is equal to $\exp(\beta)-1$. For the OLS specifications, $E[y_{it}|d_{it};\alpha_i,v_t] = \beta \cdot divest_{i,t} + \alpha_i + v_t$. Accordingly, the percentage change in the expected number of counts is equal to $\frac{\beta}{E[y_{it}|d_{it}=0;\alpha_i,v_t]}$.

events, the upper bound of the 95 percent confidence interval is 0.04; for fires, it is 0.11; for escalated enforcement, it is 0.07.

For the radiation exposure equations, however, the effects are small. The coefficient on divestiture for collective worker exposure is -11, which is only 7 percent of the mean value. The coefficient on divestiture for average worker exposure is essentially zero.

Overall, it appears that safety records did not worsen, despite the increased generation brought about by divestiture. Furthermore, there is weak evidence that safety records improved. These results match anecdotal evidence that deregulation led to improved safety. Whereas the NRC had expressed concerns about plant safety following deregulation, a regional administrator said in 2001 that "[m]ost people have gotten the understanding if you do it right the first time, and you emphasize safety and managing things better, it has a positive effect on the bottom line."[26]

Several robustness checks give qualitatively similar results (table 4). Ideally, I would estimate the Poisson specification with month-of-sample (rather than month and year) effects. This likelihood function proves difficult to fit because of the large number of explanatory variables, and block-bootstrapping the standard errors (to account for clustering) proves impossible (the likelihood function frequently does not converge for the bootstrapped samples). Instead, I collapse the data to yearly observations at the plant level. Columns (1), (4), and (7) show these results, which are very similar to the monthly regressions in table 3.[27] I next estimate a conditional negative binomial with fixed effects specification in columns (2), (5), and (8).[28] This specification is sometimes used to further alleviate the over-dispersion problem in Poisson models. However, the Poisson model may be preferred, since the individual effects α_i enter the conditional negative binomial specification only in the variance

[26] Source: Wald, Matthew L. 2001. "Despite Fear, Deregulation Leaves Nuclear Reactors Working Harder, Longer and Safer." *New York Times*, February 18. The same article gives an example of how Entergy's practices improved safety: "On one of the occasions Pilgrim shut down, a warning light in the control room alerted operators to a low oil level in a pump that circulates water in the reactor... Annoyingly, the light indicated only that the oil had fallen below a certain level, and did not tell them how much was left or whether the level was still declining. Fixing the leak or putting in more oil would require shutting the plant down for days, with a revenue loss of about $500,000 a day; perhaps they should just wait to see if the plant started vibrating, before shutting the reactor, and hope that it lasted until the next stop for refueling. But they decided that the pump might fail suddenly and trigger safety systems that would make the reactor shut down automatically, not a big risk but an undesirable outcome. So they stopped it, and then found that, in fact, the remaining oil would have lasted for months. Longtime employees say Boston Edison would have done the same, but probably not what Entergy did next: set to work on designing a bigger oil reservoir and a more sophisticated monitoring system, so that the plant never has to shut again because of a similar uncertainty."

[27] The point estimates for the monthly regression with month-of-sample effects are also extremely similar. I do not show these results, since the correct standard errors cannot be calculated.

[28] The fixed-effects negative binomial model begins with a Poisson specification and then assumes the Poisson parameter follows a $gamma(\exp(x_{it}B), \alpha_i)$ distribution. This implies that the variance is proportional to the mean. The α_i parameter is allowed to vary by reactor in the fixed-effects specification.

parameter. That is, this specification does not allow for heterogeneity in the mean across units (Allison and Waterman 2002).[29] Again, regressions at the monthly level are difficult to fit, and block-bootstrapped standard errors cannot be calculated. Accordingly, in columns (2), (5), and (8), I show results after collapsing the data to yearly observations at the plant level. The coefficient on divestiture is again similar to the estimated coefficient in the main specifications. The exception is the escalated enforcement equation, for which the coefficient on divestiture is smaller than in the Poisson regressions. This is likely because the negative binomial specification does not allow for heterogeneity in the mean across units.[30] Finally, I show OLS specifications with month-of-sample effects, reactor fixed effects, and clustered (by plant/year) standard errors. The coefficients on divestiture are negative and marginally statistically significant. To compare the magnitude in the OLS specifications with the magnitude in the count specifications, I again show the percentage change in the expected number of counts attributable to divestiture for all regressions.

For all future regressions using the three count variables, I show results for the Poisson specification with month and year effects. This specification is preferred over the negative binomial model (which does not allow heterogeneity in the mean across reactors), and over the OLS specification (which is at best only a linear approximation). Results for these alternative specifications are given in Appendix 2.

4.4 Heterogeneity

I next explore whether heterogeneity can also be observed across reactor fixed characteristics (table 5). Following Davis and Wolfram, I divide reactors according to type (BWR vs. PWR), age, and design capacity. I define newer reactors (51 of 103) as those entering commerical operations in 1979 or later. I define large reactors (49 of 103) as those with current capacity of at least 1000 MW. For all five safety measures, the main results presented previously in table 3 generally hold within the subgroups. The coefficient on divestiture is generally not statistically different for BWR versus PWR reactors. However, there is some evidence that newer and larger reactors improved more, particularly for initiating events and escalated enforcement.

[29] Unconditional negative binomial regressions have instead been proposed by some researchers: the individual effects α_i enter as dummy variables (Allison and Waterman 2002). This leads to an incidental parameters problem for short panels (with few time periods) and biased estimates. I estimated this unconditional negative binomial specification, with both mean dispersion parameterization and constant dispersion parameterization, and the point estimates and statistical significance were similar to the Poisson and unconditional negative binomial specifications.

[30] In a Poisson specification without fixed effects, I also obtain a result that is smaller in magnitude.

4.5 State-Level Selection

Next, following Davis and Wolfram (2011), I exclude a series of states to address potential selection concerns. First I exclude Michigan, where some but not all reactors were divested (in all other states, either all or none were divested). Second, I exclude California, where fossil fuel plants but not nuclear plants were divested. Furthermore, one of the nuclear plants (Diablo Canyon) is subject to strong incentive regulations. Third, I exclude Iowa and Wisconsin, where reactors were divested but the electricity market was not deregulated. Finally, I exclude the Northeast, where most divestitures occurred, to see if unobserved regional differences drive the results.[31] For all four specifications (table 6), the results are fairly robust. The coefficient on divestiture is always negative, and the magnitudes are largely unchanged from the main specification (with the exception of column (4), which excludes the Northeast and in which the estimated coefficients are mostly larger).

4.6 Spillovers and Consolidation

Narrative evidence suggests that there have been spillovers of safety practices across plants, including to the companies operating non-divested plants.[32] There are several organizations that facilitate knowledge-sharing across the plants: the World Association of Nuclear Operators (WANO), the U.S.-based Institute of Nuclear Power Operations (INPO), the Electric Power Research Institute (EPRI), and EUCG. INPO, for institute, shares best practices regarding safety; EUCG shares (blinded) financial and management strategies with its members. If the owners of divested plants share their practices with the owners of non-divested plants, the regression results above will give a lower bound on the overall effect of divestiture. The control group (non-divested plants) will have been impacted by divestiture, implying a poor counterfactual. If the control group improves following divestiture, the coefficient on the divestiture dummy will be smaller than the true effect on the divested plants. Additionally, the regression results will fail to capture the effect on the non-divested plants. It is not

[31] Interestingly, Northeast Utilities adopted a strategy of cutting costs (in anticipation of deregulation, and prior to any divestitures) that later proved to compromise safety. An L.A. Times article in 1996 described an industry leader saying that "Northeast Utilities showed the industry how short-term cost-saving measures lead to safety violations and Nuclear Regulatory Commission scrutiny, which adds huge expense even if the nuclear plant keeps operating" (Source: Kraul, Chris. 1996. "Twilight of the Nukes?" *Los Angeles Times*, October 13).

[32] For instance, a 1999 Wall Street Journal article cited efficiency gains at Arkansas Nuclear One and Sequoyah, two non-divested plants. In both cases, companies were moving to doing more maintenance while the plants were online. Arkansas Nuclear One cited improved management learned from its sister plants owned by Entergy (Schiffler, Antje. 1999. "Power Plants Feel Pressure to Cut Outage Time." *Wall Street Journal*, November 15). A 2003 MIT study argued that "[t]he means of improvement [in capacity factors] include independent peer review and the feedback of operating experience at reactor fleets worldwide, so that all operators become aware of mishaps that occur."

possible to empirically test for these spillovers across all plants. There is some suggestive evidence that this has occurred; for instance, safety records have improved nationwide in the last decade. This could also, however, be the result of other changes (for instance, more stringent NRC regulations).

It is possible to look for evidence of one type of spillover: intra-firm spillovers between divested and non-divested plants. Three companies currently own both divested and non-divested reactors: Entergy, Dominion, and NextEra (formerly FPL Group). I add a dummy variable to the main OLS specification, equal to one for each reactor that is not divested but is owned by one of these three companies (a total of thirteen reactors). These regressions compare three groups of reactors: divested units, units that were not divested but are owned by a company with other divested units, and units that were not divested and whose parent company owns no divested units. Results are given in table 7. The coefficient on divestiture is similar to the main results for each safety measure. For the co-ownership variable, results are negative but not significantly different from zero. Note however, that this regression can only identify spillovers within companies relative to those across companies. Indeed, if spillovers across companies are as large as spillovers within companies, this coefficient would be zero. Unfortunately, it is not possible to test for spillovers across companies.

Similarly, one might expect consolidation to have an effect. In 1996, before electricity deregulation, there were 44 companies operating the 66 plants in the U.S. In 2009, there were 26 companies operating the same plants in the U.S. Exelon currently owns the largest number of units (17). Consolidation could improve plant operating records (both safety and reliability) in a number of ways: through intra-firm spillovers, economies of scale (for instance, the ability to move maintenance teams from plant to plant), and through reputation effects (an incident at one plant leading to increased scrutiny at all plants). While Davis and Wolfram (2011) find some evidence of a consolidation effect for capacity factors, I do not find strong evidence for safety records (table 8). In these regressions, the coefficient on divestiture remains negative, and the coefficient on consolidation is small and not statistically different from zero at the 5 percent level in any equation.

4.7 Learning

There is some evidence that the benefits of divestiture would increase over time, both because some plant modifications would take time[33] and because the companies would learn over time.

[33] An Entergy spokesman was cited in 2003 as saying that Entergy was "able to make some fixes quickly, while turning around operations at other units will take more time." Source: Ryan, Margaret L., Tom Harrison, Jenny Weil, Daniel Horner, Elaine Hiruo and Steve Dolley. 2004. "Reports Show Costs Push Upward for U.S. Operators in 2003." *Nucleonics Week* 45(39).

The time series plots (figures 1 through 6) showed some evidence of a change in the trend of safety records at divested relative to non-divested plants. Accordingly, I add linear trends pre- and post-divestiture at divested plants (because of the year effects, there is insufficient variation to test for national trends at all plants), with results in table 9. The coefficient on the linear trend is scaled to represent a three-year change. Overall, trends post-divestiture are negative, consistent with learning.

4.8 Simultaneity with Generation

The estimates given above should be treated as the reduced form effects of divestiture on safety; they include the indirect effects of divestiture on safety through generation. In particular, there is likely simultaneity between safety and generation. For instance, if a fire occurs in the turbine area, the plant must shut down until repairs can be made; in this case, unsafe events lead to lower generation. On the other hand, if a plant shuts down (for some exogenous reason), it is less likely to have a fire, because the turbine is not moving. In this case, increased generation leads to more unsafe events. Throughout this section, I focus on initiating events and fires, for which this intuition is most applicable. It is less clear that there is simultaneity between generation and escalated enforcement (which are the product of a long-term evaluation by the NRC) or between generation and radiation exposure.

Unfortunately, because I do not observe the generation level at a plant prior to a fire (only the total generation for a day or a month, which is conditional on whether a fire occurred), I cannot empirically separate the effect of generation on safety versus the effect of safety on generation.

The intuition can be represented by the following system of equations, which assumes a simple linear process:

$$s = \alpha_1 + \beta_1 \cdot d + \gamma_1 \cdot g + \varepsilon_1 \tag{12}$$

$$g = \alpha_2 + \beta_2 \cdot d + \gamma_2 \cdot s + \varepsilon_2 \tag{13}$$

Here s is an unsafe event, g is generation, and d is a divestiture dummy (the variable of interest). The two γ coefficients cannot be estimated econometrically for this system, unless there is an instrumental variable for each equation. Unfortunately, there are no credible candidates for such instruments. Refueling outages, for instance, might affect unsafe events only through their impact on generation, but refueling outages occur at the same time as other planned maintenance, which is certainly correlated with safety. The reduced form equations can be derived by re-arranging the above equations as follows:

$$s = \frac{\alpha_1 + \gamma_1 \alpha_2}{1 - \gamma_1 \gamma_2} + \frac{\beta_1 + \gamma_1 \beta_2}{1 - \gamma_1 \gamma_2} \cdot d + \frac{\varepsilon_1 + \gamma_1 \varepsilon_2}{1 - \gamma_1 \gamma_2} \tag{14}$$

$$g = \frac{\alpha_2 + \gamma_2 \alpha_1}{1 - \gamma_1 \gamma_2} + \frac{\beta_2 + \gamma_2 \beta_1}{1 - \gamma_1 \gamma_2} \cdot d + \frac{\varepsilon_2 + \gamma_2 \varepsilon_1}{1 - \gamma_1 \gamma_2} \tag{15}$$

Estimating this system will give four coefficients, from which the six structural coefficients cannot be identified. Furthermore, if one were to estimate equations (12) and (13) separately, the estimates for each equation would be biased. For instance, it is straightforward to show that the estimate of β_1 would be biased, as a result of the simultaneity of s and g.

However, the reduced form parameters, e.g. $\frac{\beta_1+\gamma_1\beta_2}{1-\gamma_1\gamma_2}$, can be recovered, by estimating equations (14) and (15). The only assumptions needed are $E(d\varepsilon_1) = 0$ and $E(d\varepsilon_2) = 0$. The estimates given throughout the paper are indeed these reduced form parameters. These estimates are of interest in of themselves; in equation (14), they give the correlation between divestiture and safety that includes an effect via generation.

4.8.1 Bounding the Direct Effect of Divestiture on Safety

Moreover, the underlying structural parameters can be bounded given assumptions on the simultaneity of unsafe events and generation. Intuitively, the direct effect of divestiture on unsafe events could be positive or negative (as described in the modeling section), but divestiture also increases generation, thereby increasing the exposure of the plant to an event. Then the structural coefficient on divestiture will be more negative, or less positive, than the reduced form coefficient.

Furthermore, the magnitude of the structural coefficient can be bounded. Taking the preferred empirical estimate from Davis and Wolfram (2011), suppose that divestiture increases generation by approximately 10 percent. Note that the Davis and Wolfram estimate is also a reduced form coefficient, which includes the indirect effect divestiture on generation through safety. However, the difference between the reduced form and structural coefficients in this case are likely small, since unsafe events are infrequent. Accordingly, assume a direct effect of 10 percent for now; the difference between the direct and indirect effects are explored below.

Suppose the direct effect of divestiture is to reduce unsafe events by $x\%$. Also, make the neutral assumption that the elasticity of events with respect to generation time is 1: a one percent increase in generation time leads to an expected increase in unsafe events of one percent.[34] Finally, denote the total (reduced form) effect of divestiture as a reduction

[34] The elasticity could be smaller if increased generation time allows for built-up expertise. On the other

in unsafe events of $s\%$ (empirically estimated to be 15 percent for initiating events and 49 percent for fires).[35] Then the direct effect x can be calculated as follows. If the direct and indirect effects combine multiplicatively,[36] then

$$\underbrace{(1 - direct\%\Delta events)}_{direct\,effect\,on\,safety} \cdot \underbrace{(1 + \underbrace{\%\Delta generation}_{direct\,effect\,on\,gen} \cdot \underbrace{\frac{\%\Delta events}{\%\Delta generation}}_{elasticity\,of\,events\,wrt\,gen}}_{indirect\,effect\,on\,safety} = 1 - \underbrace{total\%\Delta events}_{total\,effect\,on\,safety} \tag{16}$$

$$(1 - x\%) \cdot (1 + 0.1 \cdot 1) = 1 - s\%$$

Then the direct effect of divestiture on is calculated to be -0.23 for initiating events and -0.54 for fires. Thus while divestiture leads to a total effect of a reduction of 15 percent in initiating events, the direct structural effect is a reduction of 23 percent. The difference arises from the indirect effect through generation.

4.8.2 Bounding the Direct Effect of Divestiture on Generation

A similar exercise can be performed for the effect of divestiture on generation. As described above, this is likely to very close to the total effect: there are few unsafe events in any given month, so the indirect effect of these incidents on generation is likely to be small. Suppose the direct effect of divestiture is to increase generation by $x\%$. Also, suppose the elasticity of generation with respect to initiating events is -0.016: a one percent increase in events leads to an expected decrease in generation of 0.016 percent. This assumed elasticity is derived from (1) noting that initiating events only occur in approximately 10 percent of months, and (2) assuming that an incident leads to five days of lost generation time, i.e., 13 percent of the month's generation. Similarly, the elasticity of generation with respect to fires is -0.002, from noting that fires occur in 0.7 percent of months and assuming eight days of lost generation time.[37] Finally, recall that the total (reduced form) effect of divestiture is estimated by Davis and Wolfram (2011) to be an increase in generation of 10 percent. Again assuming

hand, the elasticity could be larger if there is fatigue, for instance, of employees as generation time increases.

[35]The relevant statistics from table 3 are not the raw coefficients from each regression, but rather the percentage change in expected value.

[36]One can also assume that they combine additively ($1 - direct\%\Delta events + \%\Delta generation \cdot \frac{\%\Delta events}{\%\Delta generation} = 1 - indirect\%\Delta events$). Results are very similar for this assumption.

[37]I examined daily generation data and descriptions for twenty randomly selected fires and twenty randomly selected initiating events. The mean number of days with generation below 50 percent of capacity following the event was four for initiating events and seven for fires. There were typically a few more days of ramping with generation levels slightly lower than 100 percent of capacity.

a multiplicative combination of direct and indirect effects (where the latter includes both initiating events and fires), the direct effect of divestiture on generation is calculated to be 9 percent. This is very close to the total effect of 10 percent, because unsafe events occur fairly infrequently.

4.8.3 Normalized Regressions

An alternative approach would be to scale the safety variables by capacity factor (realized generation as a percent of total possible generation) in each month; this would be analogous to the engineering analyses that scale by reactor critical-years. This approach is not feasible at a monthly level; it leads to large outliers in months when unsafe events occur despite very low capacity factors. Regressions at the annual level largely alleviate this problem, as a smaller portion of capacity factor observations are close to zero. Table 10 shows the results from these annual regressions for all five safety variables. The intuition on simultaneity presented above applies only for initiating events and fires. However, the scaled results are of interest for escalated enforcement and radiation exposure as well; they provide information on the change in safety for given levels of annual generation.

Columns (1), (3), and (5) give results with the raw count variables and are analogous to the monthly regressions in table 3. In columns (2), (4) and (6), I normalize by capacity factor. For the count variables in Panel A, this is accomplished by including capacity factor as an exposure variable (i.e., as a regressor, with the coefficient on the logged variable equal to 1) in the Poisson specification. For the continuous variables in Panel B, the left-hand side variable is divided by capacity factor. For the results shown, I have dropped the approximately forty observations for which capacity factor is less than 0.1.[38] As expected, the effect of divestiture is larger for the normalized variables. Divestiture improved safety relative to generation, but it also increased generation; thus the net effect on safety (when not normalizing by capacity factors) is more muted. Note that the estimates for initiating events (-0.27) and fires (-0.54) are remarkably similar to the structural estimates calculated in the previous section (-0.23 and -0.54).

Overall, the bounding exercise and the normalized regressions match the intuition that the structural effect of divestiture is larger than the reduced form effect. Thus the estimates provided throughout this paper, which are reduced form coefficients, should be treated as conservative estimates.

[38]The magnitude (but not the sign) of the coefficients on escalated enforcement and the two radiation exposure variables is sensitive to the choice of this cut-off; they are closer to zero if I instead drop observations for which capacity factor is less than 0.2. However, they are still more negative than the reduced form coefficients.

5 Conclusion

Electricity deregulation in many states led to the divestiture of approximately half of all nuclear power plant reactors in the United States, beginning in the late 1990s. The theoretical model developed in this paper shows how wholesale electricity markets, by aligning cost incentives, lead nuclear power plants to improve reliability. Furthermore, where safety is correlated with reliability, divestiture is expected to lead to improved safety records.

Empirical evidence on several safety measures generally confirms this conclusion; safety did not deteriorate, and in some cases improved, following divestiture. The drop in safety incidents is estimated to be 15 percent for initiating events, 49 percent for fires, and 39 percent for escalated enforcement. While none of these effects is statistically significant at the 5 percent level, moderate positive effects can be ruled out at the 5 percent level. No effect of divestiture is found for worker radiation exposure, measured either collectively or on average. Back-of-the-envelope calculations on the direct effect of divestiture (which remove the indirect effect through generation), find larger drops in initiating events and fires. Similarly, regressions in which the variables are normalized by capacity factors give larger and more statistically significant results for all five variables.

Several caveats naturally apply. The empirical safety measures that are available may not be indicative of the risks of catastrophic events. Given the infrequency of large-scale nuclear accidents, they cannot be examined using the empirical framework presented in this paper. Also, safety problems that are uncorrelated with generation (such as on-site security and post-accident preparation) and that develop over longer time horizons (such as spent fuel storage and plant decommissioning) may worsen following plant divestiture. Future work could examine testing and preventive maintenance records for evidence on the effect of divestiture on large-scale and long-term risks. Future work could also extend the model to incorporate the dynamic choices of firms, as has been done for the literature on capacity factors at oil refineries (Chesnes 2009).

In sum, while previous work has found large increases in generation following divestiture (Davis and Wolfram 2011), this paper presents theoretical and empirical evidence that safety improved as well. Efficiency gains found for generation do not appear to have come at the cost of worsened safety records. In fact, they may have been accompanied by improvements in safety. Furthermore, the possibility of unmeasured spillovers, through best practices sharing, implies that the overall impact on safety may have been larger than is measured here.

References

[1] Allison, Paul D. and Richard P. Waterman. 2002. "Fixed-Effects Negative Binomial Regression Models." *Sociological Methodology* 32(1): 247-265.

[2] Averch, Harvey and Leland L. Johnson. 1962. "Behavior of the Firm under Regulatory Constraint." *American Economic Review* 52(5): 1052-1069.

[3] Barnett, Arnold and Mary K. Higgins. 1989. "Airline Safety: The Last Decade." *Management Science* 35(1): 1-21.

[4] Baron, David P. 1989. "Design of Regulatory Mechanisms and Institutions." *Handbook of Industrial Organization* 2(24): 1347-1447.

[5] Bier, Vicki, James Joosten, David Glyer, Jennifer Tracey, and Michael Walsh. 2001. "Deregulation and Nuclear Power Safety: What Can We Learn from Other Industries?" *The Electricity Journal* 14(4): 49-60.

[6] Chesnes, Matthew. 2009. "Capacity and Utilization Choice in the U.S. Oil Refining Industry." Working Paper.

[7] David, Paul A., Roland Maude-Griffin, and Geoffrey Rothwell. 1996. "Learning by Accident? Reductions in the Risk of Unplanned Outages in U.S. Nuclear Power Plants After Three Mile Island." *Journal of Risk and Uncertainty* 13(2), pp 175-198.

[8] Davis, Lucas. 2011. "Prospects for U.S. Nuclear Power after Fukushima." EI @ Haas Working Paper 218.

[9] Davis, Lucas and Catherine Wolfram. 2011. "Deregulation, Consolidation, and Efficiency: Evidence from U.S. Nuclear Power." EI @ Haas Working Paper 217.

[10] Eide, Steven A., Dale M. Rasmuson, and Corwin L. Atwood. 2005. "Integrated Initiating Event Performance Indicator." Idaho National Laboratory.

[11] Energy Information Adminstration. 2011. *Electric Power Annual 2009*. Washington, DC: U.S. Department of Energy.

[12] Fabrizio, Kira R., Nancy L. Rose, and Catherine D. Wolfram. (2007). "Do Markets Reduce Costs? Assessing the Impact of Regulatory Restructuring on US Electric Generation Efficiency." *American Economic Review* 97(4): 1250-1277.

[13] Feinstein, Jonathan S. 1989. "The Safety Regulation of U.S. Nuclear Power Plants: Violations, Inspections, and Abnormal Occurrences" *Journal of Political Economy* 97(1): 115-154.

[14] Galiani, Sebastian, Paul Gertler, and Ernesto Schargrodsky. 2005. "Water for Life: The Impact of the Privatization of Water Services on Child Mortality." *Journal of Political Economy* 113(1): 83-120.

[15] Golbe, Devra L. 1986. "Safety and Profits in the Airline Industry." *Journal of Industrial Economics* 34(3): 305-318.

[16] Government Accountability Office. 2008. "Nuclear Safety: NRC's Oversight of Fire Protection at U.S. Commercial Nuclear Reactor Units Could Be Strengthened." Report GAO-08-747. Washington, D.C.: U.S. Government Accountability Office.

[17] Griffin, James M. and Steven L. Puller. 2005. "A Primer on Electricity and the Economics of Deregulation." *Electricity Deregulation: Choices and Challenges*, Griffin and Puller, eds. Chicago: University of Chicago Press.

[18] Hanemann, W. Michael, Per-Olov Johansson, Bengt Kristrom, and Leif Mattsson. 1992. "Natural Resource Damages from Chernobyl." *Environmental and Resource Economics* 2(5): 523-525.

[19] Joskow, Paul L. 1997. "Restructuring, Competition and Regulatory Reform in the U.S. Electricity Sector." *Journal of Economic Perspectives 11(3)*: 119-138.

[20] Joskow, Paul L. and Richard Schmalensee. 1986. "Incentive Regulation for Electric Utilities." *Yale Journal on Regulation* 4(1): 1-49.

[21] Kahn, Alfred E. 1988. *The Economics of Regulation: Principles and Institutions.* MIT Press.

[22] Kennet, D. Mark. 1993. "Did Deregulation Affect Aircraft Engine Maintenance? An Empirical Policy Analysis." *RAND Journal of Economics* 24(4): 542-558.

[23] Knittel, Christopher R. 2002. "Alternative Regulatory Methods and Firm Efficiency: Stochastic Frontier Evidence from the U.S. Electricity Industry." *Review of Economics and Statistics* 84(3): 530-540.

[24] Laffont, Jean-Jacques and Jean Tirole. 1986. "Using Cost Observation to Regulate Firms." *Journal of Political Economy* 94(3): 614-641.

[25] Massachusetts Institute of Technology (MIT). 2003. "The Future of Nuclear Power: An Interdisciplinary MIT Study." MIT Energy Initiative.

[26] National Council on Radiation Protection and Measurements (NCRP). 2009. "Ionizing Radiation Exposure of the Population of the United States." NCRP Report No 160.

[27] Nuclear Regulatory Commission. 2010. "Information Digest." NUREG-1350, Volume 22.

[28] Rose, Nancy L. 1990. "Profitability and Product Quality: Economic Determinants of Airline Safety Performance." *Journal of Political Economy* 98(5): 944-964.

[29] Rothwell, Geoffrey S. 1989. "Stock Market Reaction to Nuclear Reactor Failures." *Contemporary Policy Issues* 7(3): 96-106.

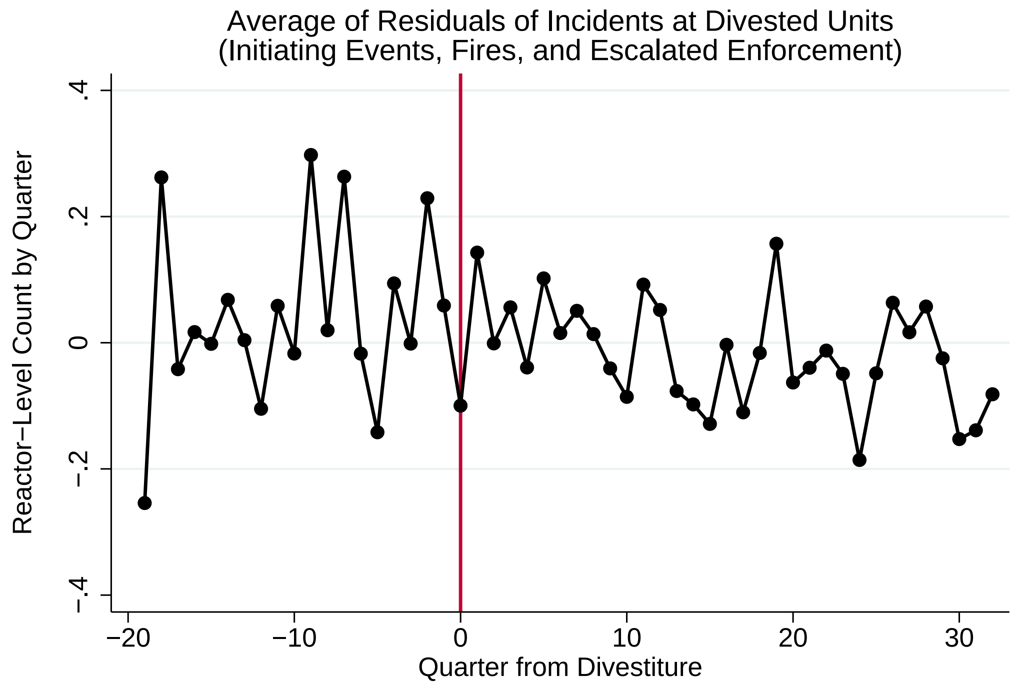
[30] Rust, John and Geoffrey Rothwell. 1995. "Optimal Response to a Shift in Regulatory Regime: the Case of the US Nuclear Power Industry." *Journal of Applied Econometrics* 10(S1): S75-S118.

[31] Verma, Kiran, Barry M. Mitnick, and Alfred A. Marcus. 1999. "Making Incentive Systems Work: Incentive Regulation in the Nuclear Power Industry." *Journal of Public Administration Research and Theory* 9(3): 395-436.

[32] White, Matthew W. 1996. "Power Struggles: Explaining Deregulatory Reforms in Electricity Markets." *Brookings Papers: Microeconomics* 201-250.

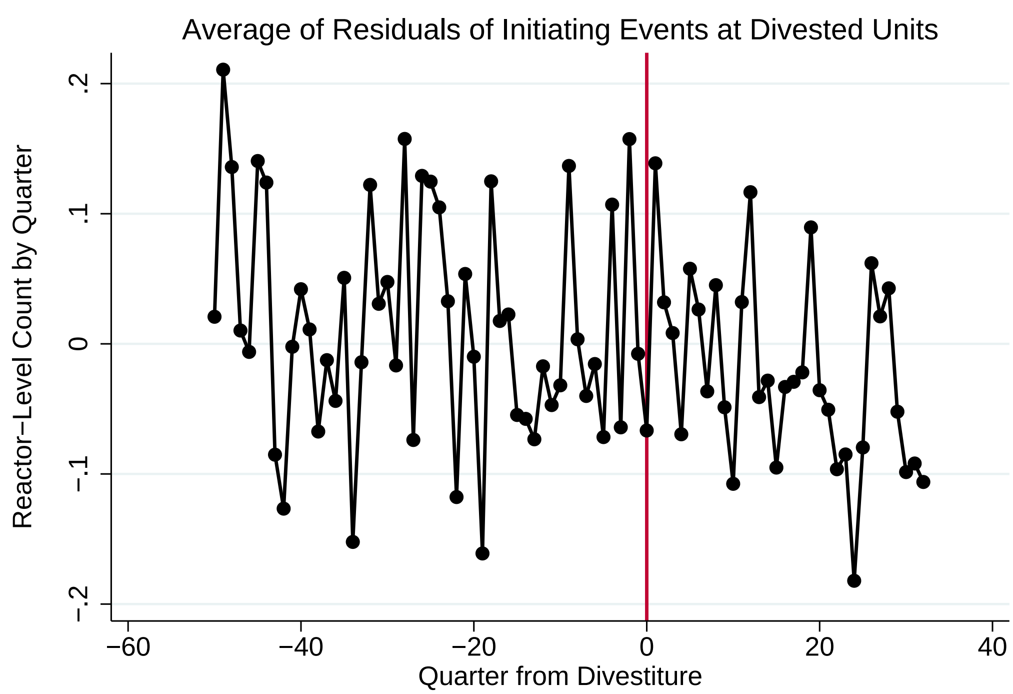
[33] Zhang, Fan. 2007. "Does Electricity Restructuring Work? Evidence from the U.S. Nuclear Energy Industry" *Journal of Industrial Economics* 55(3): 397-418.

Figure 1: Effect of Divestiture on Safety, Quarterly Event Study



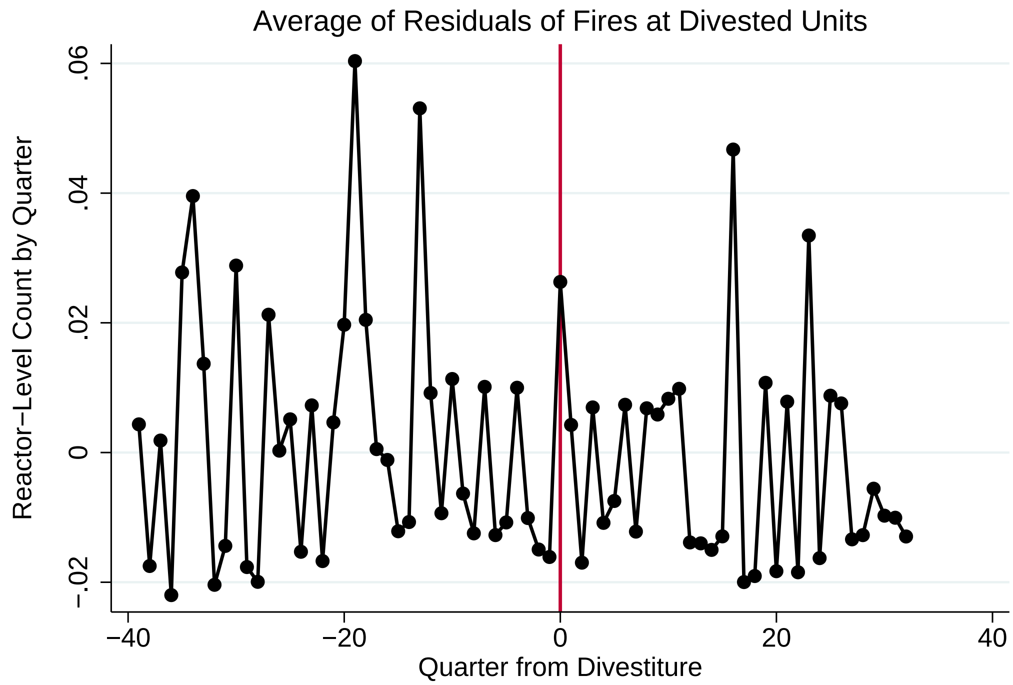
Notes: Median divestiture is in 2001. Quarter of sample and reactor effects have been removed.

Figure 2: Effect of Divestiture on Safety, Quarterly Event Study



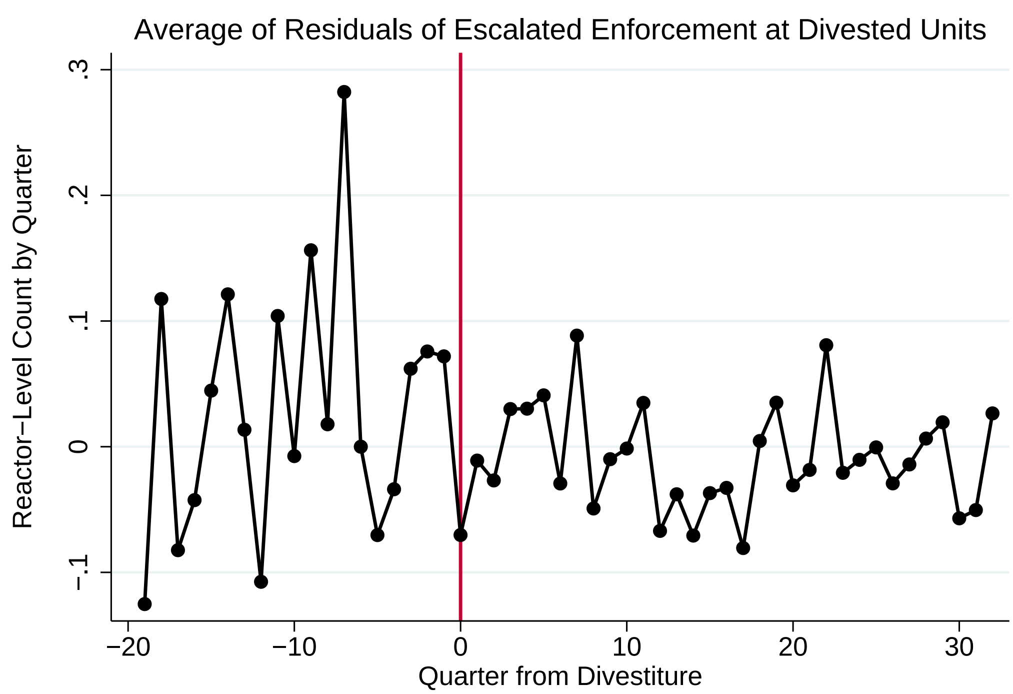
Notes: Median divestiture is in 2001. Quarter of sample and reactor effects have been removed.

Figure 3: Effect of Divestiture on Safety, Quarterly Event Study



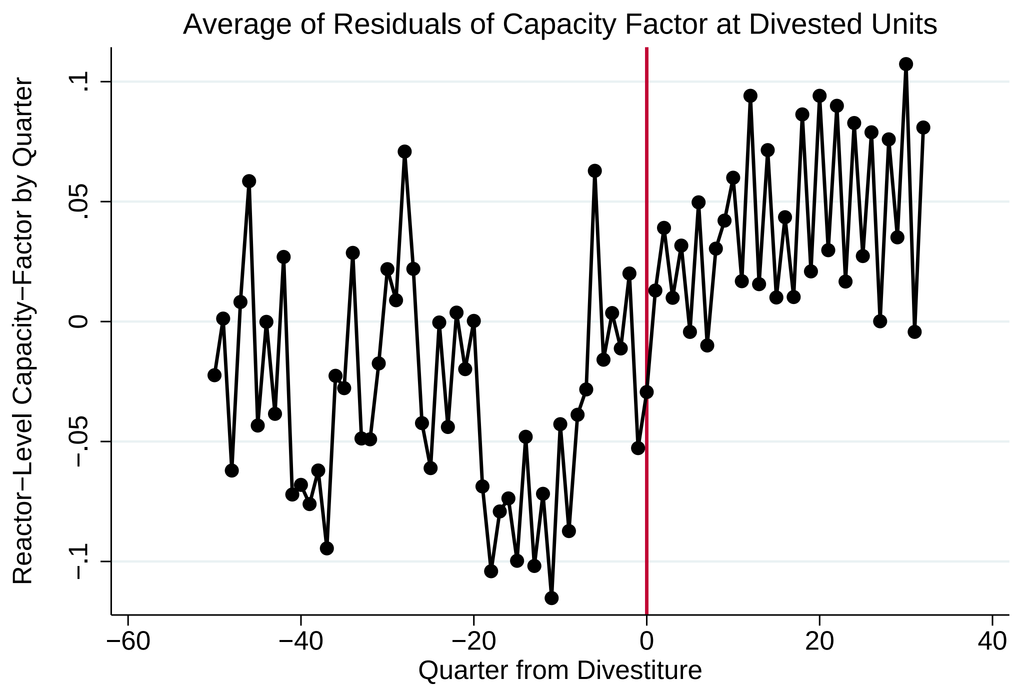
Notes: Median divestiture is in 2001. Quarter of sample and reactor effects have been removed.

Figure 4: Effect of Divestiture on Safety, Quarterly Event Study



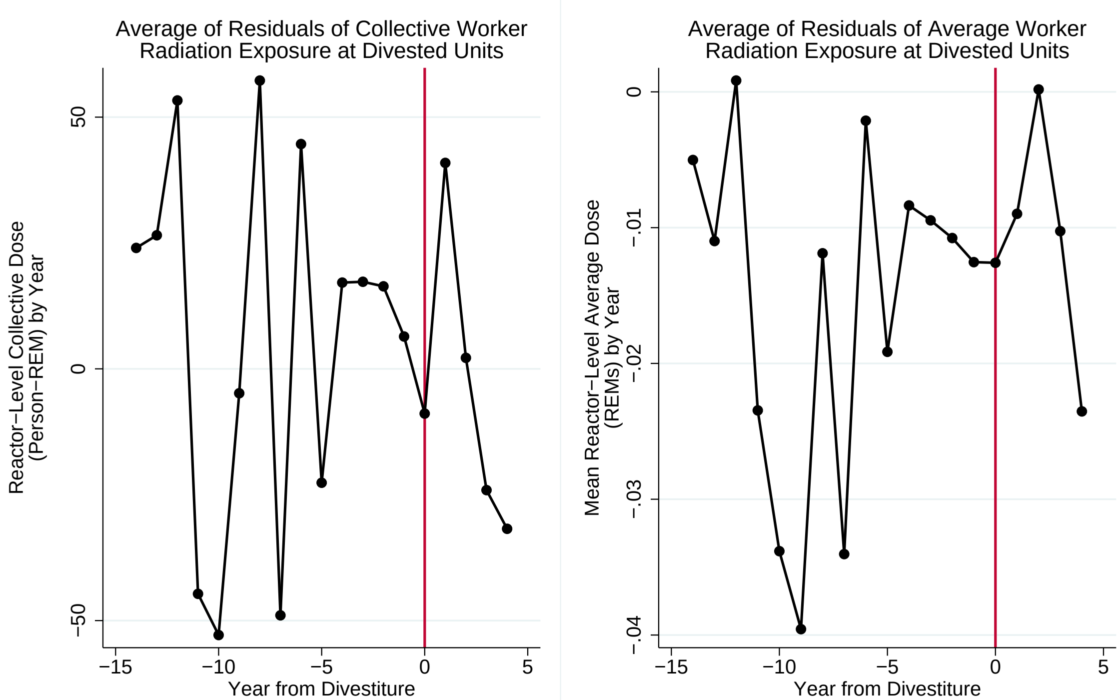
Notes: Median divestiture is in 2001. Quarter of sample and reactor effects have been removed.

Figure 5: Effect of Divestiture on Generation, Quarterly Event Study



Notes: Median divestiture is in 2001. Quarter of sample and reactor effects have been removed.

Figure 6: Effect of Divestiture on Safety, Quarterly Event Study



Notes: Median divestiture is in 2001. Year of sample and facility effects have been removed.

Notes: Median divestiture is in 2001. Year of sample and facility effects have been removed.

Table 1: Annual Reactor-Level Summary Statistics

	Mean	Std. Dev.	Min	Max
A. Safety measures:				
Initiating events	0.86	1.07	0	6
Fires	0.07	0.27	0	2
Collective worker radiation exposure	117.82	89.25	1.40	893.01
Average worker radiation exposure	0.09	0.05	0.01	0.38
Escalated enforcement	0.44	0.78	0	7
B. Reliability measures:				
Generation (million MWh)	7.27	2.13	-0.12	11.77
Capacity factor	0.88	0.16	-0.01	1.20

Notes: 103 nuclear power reactors operating in the U.S. from 1996-2009. Initiating events, fires, and escalated enforcement are count variables. Collective worker radiation exposure is measured in person-rems, and average worker radiation exposure in rems. Both radiation exposure variables are measured at the plant level, so I take a simple mean across units; also, data on these variables is only available through 2008. Generation is net, not gross, and accordingly can take on negative values. Capacity factor can similarly be negative; it can also be greater than 1 because of uprates. N = 1442 for count variables, 1338 for radiation variables.

Table 2: Pre-Treatment Observables, Monthly Level

	never divested	later divested	t-stat
A. Safety measures:			
Initiating events	0.09	0.08	1.14
	(0.33)	(0.29)	
Fires	0.007	0.005	0.93
	(0.090)	(0.068)	
Collective worker radiation exposure	233.18	248.20	-0.63
	(149.83)	(182.12)	
Average worker radiation exposure	0.18	0.19	-0.64
	(0.07)	(0.07)	
Escalated enforcement	0.07	0.08	-1.30
	(0.26)	(0.29)	
B. Reliability measures:			
Net generation (MWh)	0.58	0.47	11.26
	(0.25)	(0.31)	
Capacity factor	0.82	0.70	10.54
	(0.31)	(0.41)	

Notes: Data are for the 103 nuclear power reactors operating in the U.S. from 1996-1998, by eventual divestiture status: independent power producers versus regulated investor-owned utilities. Initiating events, fires, and escalated enforcement are count variables. Collective worker radiation exposure is measured in person-rems, and average worker radiation exposure in rems. Standard deviation are in parentheses. For the count variables (measured monthly at reactors), N = 1976 for never divested units, 1728 for later divested units. For the radiation exposure variables (measured annually at plants), N = 101 for never divested plants, 96 for later divested plants. One reactor (Watts Bar 1) starts commercial operation during this time.

Table 3: The Effect of Divestiture on Nuclear Power Plant Safety

	(1) Initiating Events	(2) Fires	(3) Escalated Enforcement	(4) Collective Worker Radiation Exposure	(5) Average Worker Radiation Exposure
Divestiture	-0.167	-0.683*	-0.378*	-11.406	0.001
	(0.107)	(0.406)	(0.227)	(19.853)	(0.008)
% change in expected value	-0.15	-0.49	-0.39	-0.07	0.005
Specification	Poisson	Poisson	Poisson	OLS	OLS
Year effects	Y	Y	Y	Y	Y
Month effects	Y	Y	Y		
Reactor effects	Y	Y	Y		
Plant effects				Y	Y
Number of observations	26882	15732	16460	1368	1368

Notes: Observation is a commercial nuclear power reactor (U.S.) in a month for the left-most three columns and a commercial nuclear power plant in a year for the right-most two columns. Divestiture is a dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by a regulated investor-owned utility. For the count specifications, the percentage change in expected value is equal to exp(coefficient) minus one; for OLS, it is equal to the coefficient divided by the mean number of counts at non-divested reactors. Initiating events, fires, and escalated enforcement are count variables. Collective worker radiation exposure is measured in person-rems, and average worker radiation exposure in rems. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009; and radiation exposure is 1988-2008. For fires and escalated enforcement, some reactors (34 and 5, respectively) are dropped in the count regressions because all observations are zero. Standard errors, bootstrapped with 500 repetitions, are clustered by plant/year in the count specifications. Stars denote 10%, 5%, and 1% significance.

Table 4: Robustness Checks: The Effect of Divestiture on Nuclear Power Plant Safety

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Initiating Events			Fires			Escalated Enforcement		
Divestiture	-0.164*	-0.167	-0.015*	-0.621*	-0.622*	-0.004*	-0.348**	-0.181	-0.015*
	(0.088)	(0.102)	(0.009)	0.3552	(0.369)	(0.002)	0.1577	(0.201)	(0.008)
% change in expected value	-0.15	-0.15	-0.21	-0.46	-0.46	-0.64	-0.29	-0.17	-0.70
Specification	Poisson	Neg Bin	OLS	Poisson	Neg Bin	OLS	Poisson	Neg Bin	OLS
Year effects	Y	Y	Y	Y	Y	Y	Y	Y	Y
Month effects			Y			Y			Y
Reactor effects			Y			Y			Y
Plant effects	Y	Y		Y	Y		Y	Y	
Number of observations	1440	1440	26882	988	988	23389	882	882	17300

Notes: Observation is a commercial nuclear power plant (U.S.) in a year for the count specifications and a reactor in a month for the OLS specifications. Divestiture is a dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by a regulated investor-owned utility. For the count specifications, the percentage change in expected value is equal to exp(coefficient) minus one; for OLS, it is equal to the coefficient divided by the mean number of counts at non-divested reactors. Sample dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; and escalated enforcement is 1996-2009. For fires and escalated enforcement, some plants (14 and 3, respectively) are dropped in the count regressions because all observations are zero. Standard errors for the OLS specification are clustered by plant/year. Stars denote 10%, 5%, and 1% significance.

Table 5: Heterogeneity by Reactor Characteristics

	(1)	(2)	(3)	(4)	(5)
	Initiating Events	Fires	Escalated Enforcement	Collective Worker Rad. Exp.	Average Worker Rad. Exp.
Divestiture, BWR	-0.084	-0.652	-0.341	-58.6*	-0.010
	(0.125)	(0.488)	(0.295)	(30.0)	(0.011)
Divestiture, PWR	-0.259*	-0.734	-0.408	38.3*	0.012
	(0.146)	(1.110)	(0.288)	(19.6)	(0.009)
Chi-squared stat	1.14	0.00	0.03	9.06***	3.01*
Divestiture, older reactors	0.039	-0.371	-0.240	-24.0	-0.003
	(0.125)	(0.459)	(0.242)	25.2	(0.009)
Divestiture, newer reactors	-0.403***	-1.181	-0.628*	9.6	0.007
	(0.148)	(1.425)	(0.347)	25.8	(0.011)
Chi-squared stat	6.88***	0.32	1.28	1.05	0.66
Divestiture, small reactors	0.077	-0.695	-0.271	-13.0	-0.009
	(0.123)	(0.488)	(0.265)	26.0	(0.010)
Divestiture, large reactors	-0.418***	-0.669	-0.539*	-9.4	0.014
	(0.147)	(0.488)	(0.317)	25.9	(0.010)
Chi-squared stat	8.89***	0.00	0.57	0.01	3.21*
Specification	Poisson	Poisson	Poisson	OLS	OLS
Year effects	Y	Y	Y	Y	Y
Month effects	Y	Y	Y		
Reactor effects	Y	Y	Y		
Plant effects				Y	Y
Number of observations	26882	15732	16460	1368	1368

Notes: A separate regression is run for each heterogeneous effect (PWR versus BWR, reactor vintage, and reactor size). Observation is a commercial nuclear power reactor (U.S.) in a month for the left-most three columns and a commercial nuclear power plant in a year for the right-most two columns. Divestiture is a dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by an investor-owned utility. I define newer reactors (51 of 103) as those entering commercial operations in 1979 or later. I define large reactors (49 of 103) as those with current capacity of at least 1000 MW. Initiating events, fires, and escalated enforcement are count variables. Collective worker radiation exposure is measured in person-rems, and average worker radiation exposure in rems. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009; and radiation exposure is 1988-2008. For fires and escalated enforcement, some reactors (34 and 5, respectively) are dropped in the count regressions because of all zero outcomes. Standard errors, bootstrapped with 500 repetitions, are clustered by plant/year in the count specifications. Stars denote 10%, 5%, and 1% significance.

Table 6: State-Level Selection

	(1)	(2)	(3)	(4)
	Excluding Michigan	Excluding California	Excluding Iowa and Wisconsin	Excluding Northeast
	A. Initiating Events			
Divestiture	-0.130	-0.178*	-0.190*	-0.338*
	(0.106)	(0.106)	(0.110)	(0.173)
Number of observations	25826	25826	25826	20603
	B. Fires			
Divestiture	-0.698	-0.693*	-0.661	-1.029
	(0.424)	(0.395)	(0.404)	(2.088)
Number of observations	14820	15048	15048	10944
	C. Escalated Enforcement			
Divestiture	-0.375	-0.389*	-0.396	-0.332
	(0.235)	(0.228)	(0.241)	(0.296)
Number of observations	15788	15788	15788	12764
	D. Collective Worker Radiation Exposure			
Divestiture	-5.760	-14.018	-12.345	-27.285
	(20.227)	(20.043)	(20.635)	(31.830)
Number of observations	1306	1326	1305	1014
	E. Average Worker Radiation Exposure			
Divestiture	0.005	0.001	-0.002	-0.014
	(0.008)	(0.008)	(0.008)	(0.011)
Number of observations	1306	1326	1305	1014

Notes: Observation is a commercial nuclear power reactor (U.S.) in a month for in sections A, B, and C; observation is a commercial nuclear power plant in a year for the sections D and E. Divestiture is a dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by an investor-owned utility. Panels A-C are Poisson specifications with year, month, and reactor effects. Panels D and E are OLS specifications with year and facility effects. Initiating events, fires, and escalated enforcement are count variables. Collective worker radiation exposure is measured in person-rems, and average worker radiation exposure in rems. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009; and radiation exposure is 1988-2008. For fires and escalated enforcement, some reactors are dropped in the count regressions because of all zero outcomes. Standard errors, bootstrapped with 500 repetitions, are clustered by plant/year in the count specifications. Stars denote 10%, 5%, and 1% significance.

Table 7: Intra-Firm Spillovers

	(1) Initiating Events	(2) Fires	(3) Escalated Enforcement	(4) Collective Worker Rad. Exp.	(5) Average Worker Rad. Exp.
Divestiture	-0.175	-0.708*	-0.461*	-17.461	0.004
	(0.112)	(0.413)	(0.235)	(19.760)	(0.008)
Co-owned	-0.044	-0.119	-0.652	-24.672	0.015
	(0.159)	(0.889)	(0.403)	(27.950)	(0.010)
Specification	Poisson	Poisson	Poisson	OLS	OLS
Year effects	Y	Y	Y	Y	Y
Month effects	Y	Y	Y		
Reactor effects	Y	Y	Y		
Plant effects				Y	Y
Number of observations	26882	15732	16460	1368	1368

Notes: Co-owned is a dummy equal to 1 if the reactor is not divested, but is owned by a company operating divested units (Dominion, Entergy, and NextEra). Thus the omitted group is non-divested reactors whose parent company operates no divested reactors. Observation is a commercial nuclear power reactor (U.S.) in a month for the left-most three columns and a commercial nuclear power plant in a year for the right-most two columns. Divestiture is a dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by a regulated investor-owned utility. Initiating events, fires, and escalated enforcement are count variables. Collective worker radiation exposure is measured in person-rems, and average worker radiation exposure in rems. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009; and radiation exposure is 1988-2008. For fires and escalated enforcement, some reactors (34 and 5, respectively) are dropped in the count regressions because of all zero outcomes. Standard errors, bootstrapped with 500 repetitions, are clustered by plant/year in the count specifications. Stars denote 10%, 5%, and 1% significance.

Table 8: Consolidation

	(1) Initiating Events	(2) Fires	(3) Escalated Enforcement	(4) Collective Worker Rad. Exp.	(5) Average Worker Rad. Exp.
Divestiture	-0.294**	-0.307	-0.412	13.775	0.004
	(0.127)	(0.526)	(0.303)	(21.018)	(0.009)
Consolidation	0.027*	-0.061	0.007	-4.810*	-0.0006
	(0.014)	(0.061)	(0.036)	(2.783)	(0.001)
Specification	Poisson	Poisson	Poisson	OLS	OLS
Year effects	Y	Y	Y	Y	Y
Month effects	Y	Y	Y		
Reactor effects	Y	Y	Y		
Plant effects				Y	Y
Number of observations	26882	15732	16460	1368	1368

Notes: Consolidation is a count variable, equal to the number of other reactors owned by the parent company. Observation is a commercial nuclear power reactor (U.S.) in a month for the left-most three columns and a commercial nuclear power plant in a year for the right-most two columns. Divestiture is a dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by a regulated investor-owned utility. Initiating events, fires, and escalated enforcement are count variables. Collective worker radiation exposure is measured in person-rems, and average worker radiation exposure in rems. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009; and radiation exposure is 1988-2008. For fires and escalated enforcement, some reactors (34 and 5, respectively) are dropped in the count regressions because of all zero outcomes. Standard errors, bootstrapped with 500 repetitions, are clustered by plant/year in the count specifications. Stars denote 10%, 5%, and 1% significance.

Table 9: Learning

	(1)	(2)	(3)	(4)	(5)
	Initiating Events	Fires	Escalated Enforce-ment	Collective Worker Rad. Exp.	Average Worker Rad. Exp.
Divestiture	-0.113	-0.645	4.462**	39.820	-0.010
	(0.473)	(2.235)	(1.926)	(63.832)	(0.041)
Linear trend pre-divestiture	-0.013	-0.036	0.338**	0.055	-0.00002
	(0.037)	(0.181)	(0.142)	(0.098)	(0.0001)
Linear trend post-divestiture	-0.175	-0.366	-0.334*	-13.542	-0.002
	(0.108)	(0.326)	(0.192)	(16.533)	(0.006)
Difference between pre- and post- trends	-0.162	-0.330	-0.672***	-13.597	-0.002
	(0.115)	(0.368)	(0.245)	(16.498)	(0.006)
Specification	Poisson	Poisson	Poisson	OLS	OLS
Year effects	Y	Y	Y	Y	Y
Month effects	Y	Y	Y		
Reactor effects	Y	Y	Y		
Plant effects				Y	Y
Number of observations	26882	15732	16460	1368	1368

Notes: Learning variable has been scaled to represent a three-year change. Observation is a commercial nuclear power reactor (U.S.) in a month for the left-most three columns and a commercial nuclear power plant in a year for the right-most two columns. Divestiture is a dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by a regulated investor-owned utility. Initiating events, fires, and escalated enforcement are count variables. Collective worker radiation exposure is measured in person-rems, and average worker radiation exposure in rems. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009; and radiation exposure is 1988-2008. Standard errors are clustered by facility/year. For fires and escalated enforcement, some reactors (34 and 5, respectively) are dropped in the count regressions because of all zero outcomes. Standard errors, bootstrapped with 500 repetitions, are clustered by plant/year in the count specifications. Stars denote 10%, 5%, and 1% significance.

Table 10: Annual Regressions with Normalized Variables

Panel A: Count Variables

	(1)	(2)	(3)	(4)	(5)	(6)
	Initiating Events		Fires		Escalated Enforcement	
Divestiture	-0.179*	-0.314***	-0.621	-0.767*	-0.348	-0.483*
	(0.109)	(0.112)	(0.410)	(0.415)	(0.237)	(0.266)
Exposure: capacity factor		Y		Y		Y
Specification	Poisson	Poisson	Poisson	Poisson	Poisson	Poisson
Year effects	Y	Y	Y	Y	Y	Y
Reactor effects	Y	Y	Y	Y	Y	Y
Number of observations	2245	2201	1311	1290	1372	1353

Notes: Observation is a reactor in a year. There are some zero capacity factor observations, which get dropped in the normalized variable regressions. Additionally, some reactors with zero events are dropped (34 in the fires equations; 5 in the escalated enforcement equations). Divestiture is the annual simple average of a monthly dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by a regulated investor-owned utility. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009. Standard errors are clustered by plant/year and bootstrapped with 500 repetitions. Stars denote 10%, 5%, and 1% significance.

Panel B: Continuous Variables

	(1)	(2)	(3)	(4)
	Collective Worker Radiation Exposure		Average Worker Radiation Exposure	
Divestiture	-11.406	-95.63**	0.001	-0.051***
	(19.853)	(43.473)	(0.008)	(0.019)
Dep. variable normalized by capacity factor		Y		Y
Specification	OLS	OLS	OLS	OLS
Year effects	Y	Y	Y	Y
Plant effects	Y	Y	Y	Y
Number of observations	1368	1349	1368	1349

Notes: Observation is a plant in a year. There are some zero capacity factor observations, which get dropped in the normalized variable regressions. Divestiture is the annual simple average of a monthly dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by a regulated investor-owned utility. Samples dates are 1988-2008. Stars denote 10%, 5%, and 1% significance.

Appendix 1: Comparative Statics for Uncorrelated Reliability and Safety

Section 3.2 gives the model for maintenance when reliability and safety are uncorrelated. The comparative statics for the firm's problem in this case are given here. The case for the social optimum is identical, but with $\theta = 1$.

Recall that the firm's problem is:

$$\max_{a^r, a^s} \quad (1 - r(a^r)) \cdot \pi - r(a^r) \cdot c^u - c^r(a^r, \pi) - s(a^s) \cdot \theta \cdot c^s - c^s(a^s, \pi) \tag{17}$$

The firm's first order conditions are:

$$-r'(a^r) \cdot \pi - r'(a^r) \cdot c^u - \frac{\partial c^r(a^r, \pi)}{\partial a^r} = 0 \tag{18}$$

$$-s'(a^s) \cdot \theta \cdot c^s - \frac{\partial c^s(a^s, \pi)}{\partial a^s} = 0 \tag{19}$$

The Hessian matrix is:

$$\begin{bmatrix} -r''(a^r) \cdot \pi - r''(a^r) \cdot c^u - \frac{\partial^2 c^r(a^r,\pi)}{\partial^2 a^r} & 0 \\ 0 & -s''(a^s) \cdot \theta \cdot c^s - \frac{\partial^2 c^s(a^s,\pi)}{\partial^2 a^s} \end{bmatrix} \tag{20}$$

The two diagonal terms are negative, so the matrix is negative definite.

Comparative statics for the firm are:

$$\begin{bmatrix} \frac{\partial a^r}{\partial \pi} & \frac{\partial a^r}{\partial c^u} & \frac{\partial a^r}{\partial \theta} \\ \frac{\partial a^s}{\partial \pi} & \frac{\partial a^s}{\partial c^u} & \frac{\partial a^s}{\partial \theta} \end{bmatrix} = -Hessian^{-1} \cdot \begin{bmatrix} \frac{\partial FOC_1}{\partial \pi} & \frac{\partial FOC_1}{\partial c^u} & \frac{\partial FOC_1}{\partial \theta} \\ \frac{\partial FOC_2}{\partial \pi} & \frac{\partial FOC_2}{\partial c^u} & \frac{\partial FOC_2}{\partial \theta} \end{bmatrix} \tag{21}$$

$$= -\begin{bmatrix} -r''(a^r) \cdot \pi - r''(a^r) \cdot c^u - \frac{\partial^2 c^r(a^r,\pi)}{\partial^2 a^r} & 0 \\ 0 & -s''(a^s) \cdot c^s - \frac{\partial^2 c^s(a^s,\pi)}{\partial^2 a^s} \end{bmatrix}^{-1}$$

$$\cdot \begin{bmatrix} -r'(a^r) - \frac{\partial^2 c^r}{\partial a^r \partial \pi} & -r'(a^r) & 0 \\ -\frac{\partial^2 c^s}{\partial a^s \partial \pi} & 0 & -s'(a^s) \cdot c^s \end{bmatrix} \tag{22}$$

Denote the above as follows, where $a < 0$, $b < 0$, the sign of c is indeterminate, $d > 0$, $e < 0$, and $f > 0$:

$$= -\begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}^{-1} \begin{bmatrix} c & d & 0 \\ e & 0 & f \end{bmatrix} \tag{23}$$

$$= -\begin{bmatrix} \frac{1}{a} & 0 \\ 0 & \frac{1}{b} \end{bmatrix} \begin{bmatrix} c & d & 0 \\ e & 0 & f \end{bmatrix} \tag{24}$$

$$= -\begin{bmatrix} \frac{c}{a} & \frac{d}{a} & 0 \\ \frac{e}{b} & 0 & \frac{f}{b} \end{bmatrix} \tag{25}$$

$$= \begin{bmatrix} ind & + & 0 \\ - & 0 & + \end{bmatrix} \tag{26}$$

Thus $\frac{\partial a^r}{\partial \pi}$ again has an indeterminate sign, $\frac{\partial a^r}{\partial c^u}$ is again positive, and $\frac{\partial a^s}{\partial \theta}$ is again positive. As expected, $\frac{\partial a^r}{\partial \theta}$ and $\frac{\partial a^s}{\partial c^u}$ are both zero: reliability maintenance does not depend on the costs of safety events and vice-versa. Note that $\frac{\partial a^s}{\partial \pi}$ is negative: potential operating profits unambiguously lower the optimal expenditures on safety maintenance. This follows from the assumption that safety maintenance requires that the plant be offline; if we instead assume $\frac{\partial^2 c^s(a^s,\pi)}{\partial a^s \partial \pi} = 0$, then potential operating profits will not affect the optimal expenditures on safety maintenance.

Appendix 2: Robustness Checks

Table A.1: Heterogeneity by Reactor Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Initiating Events			Fires			Escalated Enforcement		
Divestiture, BWR	-0.102	-0.093	-0.011	-0.574	-0.539	-0.004	-0.331	-0.237	-0.010
	(0.109)	(0.125)	(0.011)	(0.420)	(0.432)	(0.003)	(0.211)	(0.266)	(0.010)
Divestiture, PWR	-0.234**	-0.253*	-0.019*	-0.702	-0.774	-0.003	-0.362*	-0.136	-0.019*
	(0.116)	(0.136)	(0.011)	(0.528)	(0.562)	(0.002)	(0.193)	(0.242)	(0.010)
Test stat	0.90	0.97	0.39	0.04	0.13	0.22	0.02	0.11	0.47
Divestiture, older reactors	-0.059	-0.059	0.003	-0.480	-0.503	-0.002	-0.320*	-0.096	-0.016
	(0.102)	(0.118)	(0.011)	(0.399)	(0.418)	(0.002)	(0.176)	(0.223)	(0.010)
Divestiture, newer reactors	-0.339***	-0.344**	-0.035***	-0.972	-0.896	-0.005**	-0.419*	-0.379	-0.014
	(0.129)	(0.150)	(0.012)	(0.606)	(0.609)	(0.002)	(0.254)	(0.315)	(0.009)
Test stat	3.68*	2.86*	6.55**	0.54	0.33	1.17	0.13	0.69	0.02
Divestiture, small reactors	-0.049	-0.050	0.005	-0.778*	-0.699	-0.004*	-0.164	0.109	-0.017
	(0.110)	(0.127)	(0.011)	(0.462)	(0.465)	(0.002)	(0.189)	(0.231)	(0.011)
Divestiture, large reactors	-0.281**	-0.290**	-0.035***	-0.454	-0.530	-0.003	-0.600***	-0.634**	-0.013
	(0.114)	(0.134)	(0.012)	(0.464)	(0.498)	(0.002)	(0.218)	(0.291)	(0.009)
Test stat	2.76*	2.20	7.90***	0.30	0.08	0.05	2.94*	5.27**	0.09
Specification	Poisson	Neg Bin	OLS	Poisson	Neg Bin	OLS	Poisson	Neg Bin	OLS
Year effects	Y	Y	Y	Y	Y	Y	Y	Y	Y
Month effects			Y			Y			Y
Reactor effects			Y			Y			Y
Plant effects	Y	Y		Y	Y		Y	Y	
Number of observatic	1440	1440	26882	988	988	23389	882	882	17300

Notes: A separate regression is run for each heterogeneous effect (PWR versus BWR, reactor vintage, and reactor size). Observation is a commercial nuclear power plant (U.S.) in a year for the count specifications and a reactor in a month for the OLS specifications. Divestiture is a dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by an investor-owned utility. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009. For the fires and escalated enforcement equations, some plants (14 and 3, respectively) are dropped because of all zero outcomes. Test statistics is a chi-squared statistic for the count regressions and an F-statistic for the OLS regressions. Standard errors for the OLS specification are clustered by plant/year. Stars denote 10%, 5%, and 1% significance.

Table A.2: State-Level Selection

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Excluding Michigan			Excluding California			Excluding Iowa and Wisconsin			Excluding Northeast		
						A. Initiating Events						
Divestiture	-0.125	-0.130	-0.013	-0.176**	-0.178*	-0.015*	-0.184**	-0.190*	-0.017*	-0.297**	-0.308**	-0.025**
	(0.090)	(0.104)	(0.009)	(0.089)	(0.103)	(0.009)	(0.090)	(0.104)	(0.009)	(0.121)	(0.142)	(0.012)
Number of observations	1374	1374	25826	1396	1396	25826	1374	1374	25826	1068	1068	20603
						B. Fires						
Divestiture	-0.635*	-0.607	-0.004*	-0.630*	-0.622*	-0.004*	-0.597*	-0.595	-0.004*	-1.050	-0.996	-0.004*
	(0.365)	(0.380)	(0.002)	(0.360)	(0.375)	(0.002)	(0.359)	(0.373)	(0.002)	(0.613)	(0.615)	(0.002)
Number of observations	931	931	22477	950	950	22477	931	931	22477	703	703	17917
						C. Escalated Enforcement						
Divestiture	-0.344**	-0.179	-0.015*	-0.360**	-0.224	-0.015*	-0.369**	-0.223	-0.016*	-0.326	-0.060	-0.014
	(0.160)	(0.205)	(0.008)	(0.159)	(0.201)	(0.008)	(0.164)	(0.210)	(0.008)	(0.205)	(0.257)	(0.010)
Number of observations	840	840	16628	854	854	16628	840	840	16628	658	658	13268
Specification	Poisson	Neg Bin	OLS	Poisson	Neg Bin	OLS	Poisson	Neg Bin	OLS	Poisson	Neg Bin	OLS
Year effects	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Month effects			Y			Y			Y			Y
Reactor effects			Y			Y			Y			Y
Plant effects	Y	Y		Y	Y		Y	Y		Y	Y	

Notes: Observation is a commercial nuclear power plant (U.S.) in a year for the count specifications and a reactor in a month for the OLS specifications. Divestiture is a dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by an investor-owned utility. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009. For the fires and escalated enforcement equations, some plants (14 and 3, respectively) are dropped because of all zero outcomes. Standard errors for the OLS specification are clustered by plant/year. Stars denote 10%, 5%, and 1% significance.

Table A.3: Intra-Firm Spillovers

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Initiating Events			Fires			Escalated Enforcement		
Divestiture	-0.194**	-0.199*	-0.016*	-0.597	-0.629*	-0.004*	-0.490***	-0.326	-0.017**
	(0.091)	(0.106)	(0.009)	(0.366)	(0.340)	(0.002)	(0.160)	(0.206)	(0.009)
Co-owned	-0.0483	-0.065	-0.006	0.025	-0.117	-0.0007	-0.798***	-0.632*	-0.015
	(0.134)	(0.155)	(0.013)	(0.467)	(0.506)	(0.004)	(0.291)	(0.360)	(0.012)
Specification	Poisson	Neg Bin	OLS	Poisson	Neg Bin	OLS	Poisson	Neg Bin	OLS
Year effects	Y	Y	Y	Y	Y	Y	Y	Y	Y
Month effects			Y			Y			Y
Reactor effects			Y			Y			Y
Plant effects	Y	Y		Y	Y		Y	Y	
Number of observations	1440	1440	26882	988	988	23389	882	882	17300

Notes: Co-owned is a dummy equal to 1 if the reactor is not divested, but is owned by a company operating divested units (Dominion, Entergy, and NextEra). Thus the omitted group is non-divested reactors whose parent company operates no divested reactors. Observation is a commercial nuclear power plant (U.S.) in a year for the count specifications and a reactor in a month for the OLS specifications. Divestiture is a dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by an investor-owned utility. Specifications include month and year effects and reactor fixed effects. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009. For the fires and escalated enforcement equations, some plants (14 and 3, respectively) are dropped because of all zero outcomes. Standard errors for the OLS specification are clustered by plant/year. Stars denote 10%, 5%, and 1% significance.

Table A.4: Consolidation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Initiating Events			Fires			Escalated Enforcement		
Divestiture	-0.276*	-0.275**	-0.026**	-0.211	-0.241	-0.001	-0.369*	-0.161	-0.016
	(0.107)	(0.124)	(0.011)	(0.475)	(0.483)	(0.002)	(0.201)	(0.239)	(0.010)
Consolidation	0.023*	0.022	0.002	-0.066	-0.063	-0.0005*	0.004	-0.004	0.0002
	(0.012)	(0.014)	(0.001)	(0.053)	(0.054)	(0.0003)	(0.025)	(0.026)	(0.001)
Specification	Poisson	Neg Bin	OLS	Poisson	Neg Bin	OLS	Poisson	Neg Bin	OLS
Year effects	Y	Y	Y	Y	Y	Y	Y	Y	Y
Month effects			Y			Y			Y
Reactor effects			Y			Y			Y
Plant effects	Y	Y		Y	Y		Y	Y	
Number of observations	1440	1440	26882	988	988	23389	882	882	17300

Notes: Consolidation is a count variable, equal to the number of other reactors owned by the parent company. Observation is a commercial nuclear power plant (U.S.) in a year for the count specifications and a reactor in a month for the OLS specifications. Divestiture is a dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by an investor-owned utility. Specifications include month and year effects and reactor fixed effects. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009. For the fires and escalated enforcement equations, some plants (14 and 3, respectively) are dropped because of all zero outcomes. Standard errors for the OLS specification are clustered by plant/year. Stars denote 10%, 5%, and 1% significance.

Table A.5: Learning

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Initiating Events			Fires			Escalated Enforcement		
Divestiture	0.472	-0.095	-0.017	-0.626	0.096	-0.005	0.651	0.740**	0.186*
	(0.413)	(0.289)	(0.061)	(1.773)	(1.037)	(0.013)	(0.607)	(0.352)	(0.112)
Linear trend pre-divestiture	0.001	-0.0002	-0.001	-0.001	0.0004	-0.0003	0.001	0.001***	0.015*
	(0.001)	(0.0004)	(0.005)	(0.003)	(0.0015)	(0.001)	(0.001)	(0.0004)	(0.008)
Linear trend post-divestiture	-0.116	-0.145	-0.011*	-0.398	-0.371	-0.002	-0.296**	-0.185	-0.008*
	(0.089)	(0.103)	(0.006)	(0.326)	(0.326)	(0.001)	(0.140)	(0.172)	(0.005)
Difference between pre-	-0.117	-0.145	-0.009	-0.397	-0.371	-0.002	-0.297**	-0.187	-0.023**
and post- trends	(0.088)	(0.103)	(0.008)	(0.325)	(0.326)	(0.002)	(0.139)	(0.172)	(0.010)
Specification	Poisson	Neg Bin	OLS	Poisson	Neg Bin	OLS	Poisson	Neg Bin	OLS
Year effects	Y	Y	Y	Y	Y	Y	Y	Y	Y
Month effects			Y			Y			Y
Reactor effects			Y			Y			Y
Plant effects	Y	Y		Y	Y		Y	Y	
Number of observations	1440	1440	26882	988	988	23389	882	882	17300

Notes: Learning variable has been scaled to represent a three-year change. Observation is a commercial nuclear power plant (U.S.) in a year for the count specifications and a reactor in a month for the OLS specifications. Divestiture is a dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by an investor-owned utility. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009. For fires and escalated enforcement, some plants (14 and 3, respectively) are dropped in the count regressions because of all zero outcomes. Standard errors for the OLS specification are clustered by plant/year. Stars denote 10%, 5%, and 1% significance.

Table A.6: Annual Regressions with Normalized Variables

	(1)	(2)	(3)	(4)	(5)	(6)
	Initiating Events		Fires		Escalated Enforcement	
Divestiture	-0.022*	-0.053**	-0.003	-0.006	-0.014	-0.041*
	(0.013)	(0.020)	(0.002)	(0.004)	(0.011)	(0.022)
Dep. variable normalized by capacity factor		Y		Y		Y
Specification	OLS	OLS	OLS	OLS	OLS	OLS
Year effects	Y	Y	Y	Y	Y	Y
Reactor effects	Y	Y	Y	Y	Y	Y
Number of observations	2245	2201	1950	1920	1442	1423

Notes: Observation is a reactor in a year. Divestiture is the annual simple average of a monthly dummy variable equal to 1 if the reactor is owned by an independent power producer, and 0 if the reactor is owned by a regulated investor-owned utility. Initiating events, fires, and escalated enforcement are the average monthly counts in a year. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009; and radiation exposure is 1988-2008. Standard errors are clustered by plant/year. Stars denote 10%, 5%, and 1% significance.