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Abstract

Following electricity market restructuring, approximately half of all commercial U.S. nuclear power reactors were sold by price-regulated public utilities to independent power producers. At the time of the sales, some policy-makers raised concerns that these corporations would ignore safety. Others claimed that the sales would bring improved reactor management, with positive effects on safety. Using data on various safety measures and a difference-in-difference estimation strategy, I find that safety improved following ownership transfers and the removal of price regulations. Generation increased, and this does not appear to have come at the cost of public safety.

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

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1 Introduction

In the past two decades, a dramatic change to the nuclear power industry has taken place: approximately half of all U.S. nuclear power plants have been sold off by price-regulated utilities and now operate in competitive markets. Surprisingly, there is little evidence on how ownership transfers have affected safety. This paper provides the first comprehensive analysis of the impact of these nuclear power plant divestitures[1] on safety. Using data on a variety of safety measures and a difference-in-difference estimation strategy, I find no evidence that safety deteriorated; for some measures, it even improved following divestiture. Moreover, for given levels of generation, safety substantially improved. Ownership transfers led to the alignment of private incentives to increase operating efficiency, and these gains do not appear to have come at the cost of public safety.

The deregulation of electricity generation markets, begun in the late 1990s, was undertaken in part to increase efficiency and lower costs. It was thought that, under rate of return regulation, incentives were not aligned for utilities to minimize costs in the generation portion of their business. Robust empirical evidence now shows that efficiency gains were indeed realized at both fossil-fuel-fired plants and nuclear plants after the restructuring of electricity markets. Davis and Wolfram (2012) attribute a 10 percentage point increase in operating efficiency at nuclear power plants to divestiture from investor-owned utilities.

While there is now some consensus that electricity market restructuring led to the alignment of *private* costs and thus to efficiency gains, less is known about the effect of the market changes on *external* costs. Even as deregulation began in the late 1990s, some feared that the independent power producers purchasing nuclear plants would ignore safety concerns in the interest of maximizing profits. Others claimed that deregulation and consolidation would improve reactor management, and that the new owners 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]

My empirical strategy exploits the fact that only half of the reactors in the U.S. 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

[1]As described below, divestiture refers to the process whereby utilities transfer generation assets to unregulated companies, and it 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.

make the identifying assumption that this timing is exogenous to nuclear safety. To examine the validity of this assumption, I test for the possibility of selection bias. Looking at pre-divestiture safety records, I find no statistically or economically significant differences between the plants that later divest and those that remain controlled by investor-owned utilities.

Unfortunately, while catastrophic events may represent the largest social cost of nuclear power, their risk is not observable directly. I am, however, able to analyze data from the Nuclear Regulatory Commission (NRC) on five safety measures: initiating events (unplanned power changes), fires, escalated enforcement actions,[3] collective worker radiation exposure, and average worker radiation exposure. The NRC compiles these data from both operator reports and regular inspections. I choose these five measures in part because they may be the least open to manipulation by plant operators. Unplanned power changes, for instance, are not possible to hide from safety inspectors, since generation to the electrical grid is metered. Additionally, these measures represent a broad portion of the risk to plants. Initiating events cover a large portion of the internal event core damage risk to nuclear plants (Eide, Rasmuson, and Atwood 2005). Also, the NRC's authority to use escalated enforcement actions "extends to any area of licensed activity that affects the public health and safety;"[4] I thus use these as the best measure available of the failure of a reactor's operator to follow federal safety regulations.

I find that divestiture leads to a 17 percent reduction in the expected number of initiating events, a 46 percent reduction in the expected number of fires, and a 35 percent reduction in the expected number of escalated enforcement actions. While the point estimates are not very precisely estimated, the magnitude of the coefficients is economically significant. Furthermore, moderate increases in the number of events can be ruled out at the five percent level. The results are robust to a number of specification checks, including various count models and OLS estimation. For radiation exposure, I find a reduction of 25 percent for collective worker exposure and 18 percent for average worker exposure. I also examine the effect of divestiture on safety for given levels of generation. This is important because the results described above include an indirect generation effect. 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. I find larger reductions in the expected number of unsafe events for given levels of generation, and the results are statistically significant at the 1 percent level for initiating events and 5 percent level for escalated enforcement.

[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.

[4]http://www.nrc.gov/about-nrc/regulatory/enforcement/program-overview.html (Accessed July, 2011).

The results are stable across reactor type and location, alleviating concerns about selection bias. In specifications allowing for differential trends, I find that divested plants and non-divested plants were on similar trends prior to treatment. After plants are divested, they improve over time relative to non-divested plants. These results are reassuring that the difference in safety records is not driven by temporary changes immediately following divestiture.

These findings are consistent with the incentives faced by nuclear plant operators, who have strong incentives to avoid outages. Because wholesale electricity prices are much higher than variable costs for nuclear plants, any outage leads to large losses in operating profits. Thus unsafe events that lead to plant shutdowns incur private costs for plants beyond the costs of the repairs themselves. On the other hand, maintenance to prevent unsafe events is also costly if it requires a plant to shut down. Prior to divestiture, plants may have been able to pass on some of the costs of outages to their ratepayers; since this is not possible in competitive generation markets, divestiture likely changed their incentives for maintenance. Ex-ante predictions about the effect of divestiture on maintenance are not possible, for reasons discussed below. However, both anecdotal evidence and the empirical results suggest that divestiture led to improved plant management and thus to better safety records.

This paper contributes to several strands of literature. First, restructuring transformed the electricity industry in many parts of the U.S., stimulating interest among economists and policy makers in understanding the consequences of these broad market reforms. This literature is part of a larger literature on the evolution of markets following deregulation. Electricity serves as a useful empirical setting in this broader literature for a few reasons: (1) electricity is a homogeneous good, so quality changes do not confound the analysis; (2) some states deregulated while others did not, and the timing of deregulation varied. This process, while not random, has generally been thought to be exogenous to power plant operations. Several important outcomes have been analyzed in this context, including operating efficiency (Bushnell and Wolfram 2005; Davis and Wolfram 2012; Fabrizio, Rose, and Wolfram 2007; and Zhang 2007), market power (Borenstein, Bushnell, and Wolak 2002; Bushnell, Mansur, and Saravia 2008), and emissions (Fowlie 2010). This paper is the first to analyze safety, which plays a crucial role in energy production and particularly in nuclear power. Nuclear power is controversial precisely because of the potential for catastrophic events, so understanding how deregulation impacted the probability of unsafe events is crucial.

This paper also contributes to the literature on nuclear power safety. Analyses of nuclear power safety emerged following accidents at Three Mile Island and Chernobyl (e.g. David, Maude-Griffin, and Rothwell 1996, Feinstein 1989, Hanemann et al. 1992, Rothwell 1989, and Rust and Rothwell 1995), and the recent accident at the Fukushima Daiichi facility has renewed interest in understanding the risks the public faces from nuclear plants. This paper does not claim to answer the broad questions of whether the world should use nuclear power to meet its energy needs or of how safety should be regulated. It does, however, speak to how a major market transformation in the U.S. impacted almost half of the nuclear fleet.[5] Moreover, it relates to the wider literature on the structure of the nuclear power sector (including Davis 2012, MIT 2003, and MIT 2009). This sector comprises a significant portion of the U.S. electricity industry, and interest in it has been renewed in recent years because of its status as a low-carbon source of large-scale baseload electricity generation.

Third, this paper is germane to the literature on the consequences of deregulation for outcomes beyond private efficiency gains. When the airline industry was deregulated, for instance, concerns were raised about airline safety (Barnett and Higgins 1989, Golbe 1986, Kennet 1993, and Rose 1990). 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. In related work, water privatization led to concerns about increases in water-borne illness (Galiani et al. 2005). Papers in this literature are necessarily industry-specific: the interaction of private cost reductions with changes to quality or changes to external costs is highly context-dependent. However, this paper provides intuition for the mechanisms at work, some of which are generalizable beyond the nuclear power industry.

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; one example of such regulation is average-cost pricing. This cost of service 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

[5] One related paper is Verma, Mitnick and Marcus (1999), which finds mixed results for the effect of incentive regulation programs prior to divestiture on power plant safety.

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, this entry into competitive wholesale markets is the main component of deregulation expected to affect operations.

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 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 and Davis and Wolfram 2012).

An important assumption 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 (Ando and Palmer 1998). 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 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 (Griffin and Puller 2005, Joskow 1997, and White 1996). Davis and Wolfram (2012) find a slightly higher construction cost for plants that were eventually divested, however the difference is small (4 percent) and not statistically significant. Any difference in past nuclear construction costs should be time-invariant, and as such can be controlled for in empirical specifications with fixed effects. Finally, 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 three 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 affects the validity of the empirical estimation in this paper, but rather the mechanisms through which the impact of divestiture operates. Additionally, the timing of divestitures following deregulation may be endogenous. This is examined in the empirical analysis that follows.

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. There are two types of reactors in the United States, pressurized-water reactors (PWRs) and boiling-water reactors (BWRs). In both types of reactor, fuel assemblies containing enriched uranium create heat, which then produces steam to turn a turbine.

Nuclear power plants have both advantages and disadvantages relative to fossil fuels plants. Once a nuclear power plant is built, its marginal costs are low. Furthermore, it emits no carbon dioxide during operation. 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 2012). 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). An additional concern is the potential for terrorists to acquire radioactive materials or attack U.S. nuclear sites. Finally, one of the main issues raised by environmentalists is the treatment, storage, and transport of spent nuclear fuel. Spent fuel assemblies can be stored in pools or dry casks at power plants. 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. The NRC does not appear to enforce its safety regulations differentially between price-regulated and divested plants.[6] In addition to the government oversight by the NRC, nuclear power reactor safety oversight is carried out by the Institute of Nuclear Power Operations (INPO). INPO is an industry organization that conducts reactor inspections and facilitates best-practices sharing across operators. It was founded following Three Mile Island, as operators realized an incident at any one plant had the potential to lead to the closure of all plants (Rees 1994).

Finally, incentives for safety are affected by liability insurance, which is highly regulated. Both investor-owned utilities and independent power producers are regulated according to the Price-Anderson Act (PAA). The PAA has a three-tiered liability system for all facilities. 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. The federal government is responsible for all payments above 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.

2.3 Incentives and Safety

To provide context for the empirical results that follow, I discuss the incentives for safety faced by nuclear power plants; a formal derivation of this model is given in Appendix 1. Most of the costs of a nuclear power plant are fixed and are incurred at the time of construction. The plants' marginal cost is much lower than the market price of electricity generation, which is determined by the marginal cost of the marginal plant.[7] According to a recent Energy Information Administration report (EIA 2011), variable costs are 2.17 cents per kilowatt-hour for nuclear plants and 4.05 for fossil-fuel steam plants. As such, even when demand is very low, nuclear plants can earn large operating profits. Thus they generally run continuously except for outages related to repairs and refueling.[8] Any outages, planned

[6] See, e.g., the NRC's policy statement in the Federal Register regarding electricity market restructuring: "Final Policy Statement on the Restructuring and Economic Deregulation of the Electric Utility Industry." *Federal Register* 62:160 (19 August 1997): 44071-44078.

[7] For representative supply and demand curves showing nuclear marginal costs compared to fossil fuel costs, see Mansur (2008) or Griffin and Puller (2005).

[8] Vary rarely, nuclear plants are asked to reduce generation to preserve stability on the electrical grid.

or unplanned, lead to large losses of operating profits.[9] Maintenance decisions are thus, in part, a trade-off between incurring downtime for plant repairs and preventing unplanned outages. This trade-off is less relevant if maintenance can be conducted while the plant is still generating.

Consider a profit-maximizing plant choosing a level of maintenance, which affects either reliability (i.e., avoiding unplanned outages), safety, or both. The costs of unreliability are private (limited to lost revenues for the plant) while safety costs are social (representing risk to the general public).[10] In many cases, the maintenance that reduces outages has complementarities with safety (MIT 2003). The firm chooses the level of maintenance that equates private marginal benefits (e.g., avoiding unplanned outages) with private marginal costs (maintenance costs as well as foregone revenues if the plant must be down for repairs). Since not all safety costs are internalized, the firm chooses a lower level of safety maintenance than is socially optimal. Furthermore, if the same maintenance improves both reliability and safety, the sub-optimal level of maintenance leads to socially sub-optimal levels of both reliability and safety. If, however, reliability maintenance and safety maintenance are unrelated, the firm will choose the socially optimal level of reliability but a sub-optimal level of safety.[11]

The incentives are less clear under rate of return regulation. As described in section 2.1, prices in regulated electricity markets are set so that monopoly utilities recover their costs. Variable costs are passed on to rate payers, and utilities are additionally allowed a fair rate-of-return on their 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. In practice regulation usually involves some incentives for generators, but utilities are typically able to pass on to consumers a greater portion of their costs than are independent power producers.

In regulated environments, when a 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. Thus the incentives to avoid unplanned outages

[9] There is potential for the owner of a nuclear power plant to use outages 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 has a firm contract to sell, the owner will 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.

[10] Indeed, liability for nuclear power plants is capped in the U.S. under the Price-Anderson Act described in section 2.2.

[11] It should be noted that the Nuclear Regulatory Commission sets standards on safety-related equipment; if the equipment malfunctions, the plant must shut down. Any maintenance on equipment the NRC observes and regulates is therefore related to generation.

may be lower at a plant operating under rate-of-return regulation. In the short term, this is mitigated by the ability of the regulated plant to pass on its maintenance costs. In the long term, however, a deregulated plant may have a greater incentive to improve technical efficiency to lower maintenance costs.

As described in section 2.1, a key argument for electricity deregulation was to increase efficiency by aligning cost incentives and correcting agency problems. Davis and Wolfram (2012) find that reactors are available to generate for a significantly higher percentage of the time following divestiture. This improved operating efficiency appears to have come in the form of shorter refueling outages, enabled by changes in management practices. 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.[12]

Where practices that improve reliability also improve safety, divested plants may have similarly improved safety records. For instance, unplanned outages and power changes, which represent both reliability and safety costs, might be expected to fall following divestiture. This possibility is explored in the empirical section of this paper. On the other hand, safety incidents that do not affect plant reliability may not fall after divestiture. In the case where safety and reliability are uncorrelated, the effect of divestiture on safety will depend on whether the divested plant internalizes more or less of the cost of a safety event. Liability under the Price-Anderson Act does not differentiate between plants owned by investor-owned utilities and those owned by independent power producers. However, divested plants could internalize more or less of the cost of a safety event if, for instance, they are subject to a differential level of public scrutiny following an accident or place differential value on reputation.[13]

As described in section 2.2, the Nuclear Regulatory Commission regulates nuclear safety in the U.S., and INPO is an industry self-regulation organization. With perfect information and regulatory oversight, the socially optimal level of safety could be achieved in both the price-regulated and competitive generation markets. Note that there is still room for safety to improve following divestiture: if divested plants attain greater technical efficiency because of the alignment of cost incentives for reliability, the socially optimal level of maintenance would be higher.

In addition to the framework I present here, two theoretical models could be applied under

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

[13] The empirical portion of this paper examines whether consolidation affected safety records: companies that own many plants may internalize more safety costs if an incident at one plant leads to scrutiny at all plants.

price regulation: (1) the Averch-Johnson (1962) model, 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. If the allowed rate-of-return on investment is higher than the firm's cost of capital, the firm over-invests in capital relative to labor. The Averch-Johnson effect may explain the construction of nuclear power plants, but it is likely not relevant in the operation 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 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 are unobservable to public utilities commissions, since outages and accidents are stochastic. A manager could exert minimal effort while blaming outages and accidents on bad luck. In the case of nuclear plants 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.

Overall, the impact of deregulation and divestiture on plant safety is theoretically ambiguous. It depends crucially on a number of issues, including (1) whether state regulators allowed the monopoly utility prior to divestiture to pass on maintenance costs and/or replacement power costs; (2) whether maintenance for reliability has additional safety benefits; (3) whether divested plants internalize more or less of the cost of safety events; and (4) the level of federal[14] safety regulations. Since many of these factors are unobservable, I next turn to empirical evidence.

[14] All safety regulations are administered at the federal level. However, public scrutiny may vary across states.

3 Data

3.1 Power Plant Safety

For the empirical analysis, I compile data on a variety of risks to nuclear plants. The Nuclear Regulatory Commission (NRC) tracks a number of safety measures for all reactors in the United States. Reactor operators are required, under the Code of Federal Regulations (10 C.F.R. §50), 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. These 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 such as on-site 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 for this study:

- 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 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 several categories, such as "stuck open safety relief valve" or "loss of feedwater." One advantage of analyzing initiating events is that they represent a significant portion of the known internal risk to plants (Eide, Rasmuson, and Atwood 2005). These reactors trips are frequently used as a summary measure of reactor safety. They indicate that some safety system was triggered, and the rapid power-down can itself subject the plant to additional risk (David, Maude-Griffin, and Rothwell 1996). 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.

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, and whether a safety alert was declared. Following an extensive fire at the Browns Ferry plant in 1975, 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 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 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 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)." Plants 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.[15] Monitoring procedures vary over time, but details of the regulation are given by 10 C.F.R. §20, "Standards for Protection against Radiation," 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.[16] Data are at the annual facility level, in contrast to the other measures. Reporting procedures at plants with both operational reactors and permanently shut-down reactors vary: at some facilities, radiation exposure is reported separately for each reactor, whereas at some facilities they are reported in a combined measure. I drop observations that combine operational and

[15]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.

[16]The collective exposure measure, summing across workers, may be the most relevant measure of overall exposure. If, however, there are nonlinearities in the dose response function, then the average exposure for individual workers is also of interest.

permanently shut-down reactors.

A final measure of interest for safety is on "escalated enforcement," and is available in the form of the 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,[17] 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. Currently, the NRC evaluates seven areas of safety: initiating events, mitigating systems, barrier integrity, emergency preparedness, occupational radiation safety, public radiation safety, and security. 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. 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.

Unfortunately, the potential for catastrophic failure at a nuclear power reactor is not directly observable. I use these five measures because they are indicative of how well a plant is being maintained and how much risk the plant faces. As described above, initiating events represent a large portion of the known internal risk to plants and are widely used as a summary statistic of safety. Escalated enforcement represents the best available knowledge of the NRC about risk relating to a broad set of safety concerns. A second feature of the measures used is that safety along these dimensions is positively correlated with the plants' ability to generate electricity, matching the intuition described in section 2.3. However, for safety concerns that are not correlated with the ability of the plant to sell electricity, there is the possibility that divestiture will lead to increased risk. Two examples of these safety concerns might be maintenance of spent fuel storage and on-site security. However, it is important to note that if the NRC observes these actions and can shut down plants that violate regulations, this risk will also be correlated with the plants' ability to generate.

A third feature of the variables used in this analysis that is they represent measures it would be difficult for plant operators to hide or manipulate. However, to examine the possibility that divested plants are more likely to hide safety concerns, I have collected two additional measures. The NRC can initiate escalated enforcement procedures for violation of 10 C.F.R. §50.9, "Completeness and accuracy of information," if it determines that a plant operator withheld information. Escalated enforcement is also initiated for violation of 10

[17]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.

C.F.R. §50.7, "Employee protection," when plant operators discriminate against workers who raise safety concerns. These violations are infrequent, making empirical analysis difficult. However, as shown in Appendix 2, I find that divestiture is associated with a lower rate of both types of violation, alleviating concerns about deregulated plants hiding safety concerns. Overall, the safety measures I use are thus indicative of the risk of catastrophic events. These measures may miss other types of catastrophic risk. However, for the measures used in this paper to not be informative of some other risk to plants, it would need to be the case that the risk was not positively correlated with my measures (e.g., required separate maintenance procedures), was not correlated with generation (so that the plants incentives were not aligned), and was either not observed or not enforced by the NRC.

3.2 Generation and Divestitures

Generation data, from Davis and Wolfram (2012), are published in 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. I include only reactors operating as of January 1, 2000; this excludes a few reactors that were closed during the 1980s and 1990s.[18] To calculate capacity factor, I normalize generation by reactor design capacity. 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, also from Davis and Wolfram (2012), are compiled from the EIA and cross-checked against SEC filings. For the empirical analysis that follows, I focus on these divestiture dates rather than deregulation dates. Since divestiture and deregulation are highly correlated for nuclear plants, I cannot separately identify the effect of regulation changes and ownership changes. I focus on changes in ownership, for which the timing can be more precisely defined than for changes in electricity market legislation; the related literature disagrees on which dates to use for electricity deregulation.[19]

3.3 Summary Statistics and Pre-Treatment Observables

Table 1 gives summary statistics on the five safety measures of interest plus generation and capacity factor for all 103 power reactors used in my analysis.[20] The average reactor has

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

[19]See section 4.6 for a discussion of the timing of deregulation versus divestitures.

[20]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.

slightly fewer than one initiating event per year. Fires are quite rare. Worker radiation exposure averages 116 person-REMs per year. In 2008, this corresponded to roughly 1,300 workers per facility with an average dose of 0.1 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 factor can be negative, since generation measured is net, rather than gross. It can also be 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. Observations are annual, and test statistics are adjusted for clustering at the plant level. 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.[21] Panel B shows that reliability measures are statistically different at the 5 percent level; plants that were later divested have lower generation levels and capacity factors. As Davis and Wolfram (2012) 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.

Appendix 2 gives tests for differences in observable fixed reactor characteristics, previously analyzed in Davis and Wolfram (2012). There is a statistically significant difference in the proportion of boiling water reactors (BWRs) divested versus pressurized water reactors (PWRs). As such, I will test whether the effect of divestiture is robust to considering each type separately. There is no significant difference in age, capacity, number of reactors at each plant, or manufacturer (with the exception of reactors made by General Electric). There is a difference in the location of the divested facilities; this is not surprising, given the regional differences in deregulation patterns. To address concerns about selection bias, I later examine the robustness of the main results to excluding certain states and regions. Finally, no statistically significant difference is seen for maximum generating capacity, a measure that incorporates uprates and should be positively correlated with capital investment (Davis and Wolfram 2012). This further alleviates concerns about selection bias.

[21] The regressions in section 4.8, "Dynamic Effects" also test for differences in pre-treatment trends.

4 Empirical Evidence

4.1 Graphical Analysis

First, I plot an event study graph of the effect of divestiture on each safety measure at the quarterly level for all plants, intended to motivate the regressions that follow. This plot has the advantage of allowing me to examine pre-treatment trends in the number of unsafe events. While table 2 showed no difference in the pre-divestiture mean levels of unsafe events, this plot looks more flexibly at trends. Specifically, I plot the coefficients β_j from the following regression:

$$event_{i,t} = \sum_{j=-19}^{32} \beta_j \cdot 1[\tau_{i,t} = j]_{i,t} + v_t + \varepsilon_{i,t}$$

where $\tau_{i,t}$ denotes the quarter relative to divestiture, with $\tau_{i,-19}$ denoting nineteen quarters prior to divestiture, $\tau_{i,0}$ denoting the quarter of divestiture, etc.[22] The dummy variables v_t are quarter-of-sample effects. Thus the plotted coefficients β_j compare case reactors to the control reactors that never divest, net of time effects. The time effects play an important role, as unsafe events have generally been trending down; not including them would thus overstate the effect of divestiture. Figure 1 shows this for the sum of the three count variables: initiating events, fires, and escalated enforcement.[23] The figure additionally shows a lowess smoother in the pre-divestiture and post-divestiture periods in dashed grey lines. 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, any reduction in the mean will also imply a reduction in the variance.

4.2 Regression Analysis

I next provide formal tests of the effect of divestiture on safety by regressing the safety measure on a divestiture dummy and a set of reactor fixed effects and year effects. For the three

[22] The plot only shows event quarters for which there are at least 100 observations on divested units (approximately 70 percent of the full sample of divested units). Thus, while it is not a balanced panel, the sample does not change much.

[23] Summing across the three variables is an imperfect measure, since some double-counting is involved. For instance, a fire may set off an initiating event, or a severe initiating event may trigger escalated enforcement actions. As such, this measure is meant merely to serve as an illustration. The empirical analysis that follows considers each variable separately. Appendix 2 shows the plots for each individual type of event.

count variables (initiating events, fires, and escalated enforcement), the preferred specification is an unconditional negative binomial.[24] OLS is not expected to perform well given the count nature of these variables, although OLS results are shown along with other robustness checks. The negative binomial specification is preferred over a Poisson regression, which is subject to faulty inference if the data are overdispersed.[25] Poisson regression results are shown in the robustness checks. For specifications using radiation exposure, OLS regressions are used since radiation exposure is a continuous variable. These data are collected by plant rather than reactor, so I include facility fixed effects. For all specifications, standard errors are clustered at the plant level to allow for arbitrary correlation across reactors within a plant and across time.

One limitation of the estimates given in the previous two equations is that they are for the net effect of divestiture on safety, and are composed of two effects: the direct effect of divestiture plus an indirect effect through generation. That is, since the plants are operating for a greater percentage of the time, they may be more exposed to unsafe events. Hence an alternative outcome of interest is not the overall effect on safety, but rather the effect on the number of unsafe events for a given level of generation. One way to allow for this possibility empirically is to scale the safety variables by capacity factor (realized generation as a percent of design capacity) in each year; this is analogous to the engineering analyses that scale by reactor critical-years. This approach is not feasible at a monthly level; noise is introduced by large outliers in months when unsafe events occur despite very low capacity factors. These outliers can occur, for instance, if an unsafe event occurs early in the month and is then followed by an extended outage. Regressions at the annual level largely alleviate this problem; they smooth across months with low capacity factors. As such, all regressions are run at the annual level. For the results shown, I have dropped the approximately thirty observations for which capacity factor is less than 0.01.[26] For the count variables, the normalization is

[24] For an unconditional negative binomial specification, the individual effects α_i enter as dummy variables. This can leads to an incidental parameters problem for short panels, although simulations have found the resulting bias to be small (Allison and Waterman 2002). Conditional negative binomial specifications are not subject to an incidental parameters problem, however they have the unfortunate feature of allowing for heterogeneity across units only in the variance, and not in the mean. These specifications are shown in the robustness checks.

[25] The Poisson process assumes equality of the mean and variance, whereas in empirical settings the variance is often larger than the mean. This overdispersion leads to faulty inference (Type I error), 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. Overdispersion tests, available upon request, indicate overdispersion for initiating events (with dispersion parameter approximately 0.2 to 0.3). They fail to reject equidispersion for fires, with dispersion parameter less than 0.01. The tests are inconclusive for escalated enforcement, with dispersion parameter between 0 and 0.1.

[26] For comparison, I have also estimated the non-normalized regressions dropping these observations. Results, shown in Appendix 2, are similar to the main results in panel A of table 3.

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 negative binomial specification. For the continuous variables, the left-hand side variable is divided by capacity factor.

Results for both normalized and non-normalized outcome variables are given in table 3. Panel A shows the total effect of divestiture on safety, whereas panel B shows the effect for a given capacity factor. 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 all regressions.[27] For all five of the safety measures, the coefficient on divestiture is negative in panel A. For initiating events, the coefficient is -0.19; for fires, the coefficient is -0.62; and for escalated enforcement, the coefficient is -0.43. For collective worker radiation exposure, divestiture is associated with a drop of 42 person-rems; average exposure drops by 0.03 rems. While the point estimates are not precisely estimated, the magnitude of the coefficient is economically significant for all five measures. For initiating events, for instance, divestiture leads to a 17 percent reduction in the expected monthly event count. For fires, the change is -46 percent, and for escalated enforcement the change is -35 percent. Furthermore, some moderate positive effects can be ruled out at the 5 percent level: for initiating events and escalated enforcement, the upper bound of the 95 percent confidence interval is 0.06.

When the dependent variable is scaled by capacity factor (panel B), the coefficient on divestiture is more negative. Divestiture leads to a 28 percent change in initiating events for a given capacity factor, and the coefficient is statistically significant at the 1% level. For fires, the change in expected value is 54 percent (significant at the 10 percent level), and for escalated enforcement, 42 percent (significant at the 5 percent level). For the two worker radiation exposure variables, the effect is even larger, but it is not precisely estimated.

Overall, it appears that divestitures did not lead to worsened safety records, and they may have led to some decreases in unsafe events. Moreover, divestitures increased generation, and controlling for this, safety substantially improved. Both the total effect on safety (when unscaled by capacity factor) and the effect controlling for generation are of policy interest. As such, tables throughout this paper provide estimates for both outcomes.

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

[27]For the count specifications, the percentage change in the expected number of counts is equal to $\exp(\beta) - 1$. For the OLS specifications, the percentage change in the expected number of counts is equal to $\frac{\beta}{E[y_{it}|d_{it}=0;\alpha_i,v_t]}$.

on the bottom line."[28]

4.3 Simultaneity between Safety and Generation

Ideally, one would treat the simultaneity between safety and generation as a full system of equations to estimate the direct effect of divestiture on each. To understand this simultaneity, consider two cases. First, 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.[29] Throughout this section, I focus on initiating events and fires, for which this intuition is most applicable.

Unfortunately, because I do not observe the generation level at a plant prior to a fire, the direct effect of generation on safety cannot be observed separately from the direct effect of safety on generation. While I do observe the total generation for a month, this is conditional on whether a fire occurred.

The full system of equations is

$$\begin{aligned} s &= f(d, g, X) \\ g &= k(d, s, X) \end{aligned}$$

Here s is an unsafe event, g is generation, d is a divestiture dummy (the variable of interest), and X is a vector of exogenous variables. The direct effect of divestiture on each endogenous variable 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.

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

[29]Note that this analysis, which focuses on the difference in exposure when a plant is on versus off, does not account for the difference in exposure during plant ramp up and ramp down. If divested plants increase their generation time but decrease their ramping times, their exposure to a safety event could, on net, fall.

4.3.1 Calculating the Direct Effect of Divestiture on Safety

However, by making certain assumptions, the direct effect of divestiture on safety can be calculated from this system. Intuitively, the direct effect of divestiture on unsafe events could be positive or negative, but divestiture also increases generation, thereby increasing the exposure of the plant to an event. Then the direct effect on divestiture will be more negative, or less positive, than the total effect. Consider the total derivative $\frac{df}{dd} \cdot \frac{1}{s} = \frac{\partial f}{\partial d} \cdot \frac{1}{s} + \left(\frac{\partial f}{\partial g} \cdot \frac{g}{s}\right) \cdot \left(\frac{dg}{dd} \cdot \frac{1}{g}\right)$.[30] We want to know $\frac{\partial f}{\partial d}$, the direct effect, whereas what was estimated previously was $\frac{df}{dd}$, the total effect. Taking the preferred empirical estimate from Davis and Wolfram (2012), assume that $\frac{dg}{dd} \cdot \frac{1}{g} = 0.10$; divestiture increases generation by approximately 10 percent.[31] Also, make the neutral assumption that $\frac{\partial f}{\partial g} \cdot \frac{g}{s} = 1$; a one percent increase in generation time leads to an expected increase in unsafe events of one percent.[32] Finally, recall that the total effect of divestiture $\frac{\partial f}{\partial d} \cdot \frac{1}{s}$ is empirically estimated to be a reduction of 17 percent for initiating events and 46 percent for fires.[33] Then the direct effect of divestiture on unsafe events is calculated to be -0.27 for initiating events and -0.56 for fires.[34] Thus while divestiture leads to a total effect of a reduction of 17 percent in initiating events, the direct effect is a reduction of 27 percent. The difference arises from the indirect effect through generation. These results do not change much when the relationship between generation and unsafe events is allowed to vary. For $\frac{\partial f}{\partial g} \cdot \frac{g}{s} = 0.5$, the direct effect of divestiture is -0.22 for initiating events and -0.51 for fires; for $\frac{\partial f}{\partial g} \cdot \frac{g}{s} = 1.5$, the direct effects are -0.32 and -0.61. Note that these estimates are very similar to the normalized estimates calculated in the previous section (-28 percent and -54 percent).[35]

[30] For notational simplicity, I drop the year and fixed effects, which are the only exogenous variables other than divestiture. For this simplification to be valid, I assume that divestiture does not impact either the time-invariant reactor effects or the reactor-invariant year effects.

[31] Note that the Davis and Wolfram estimate is also for the total effect, which includes the indirect effect divestiture on generation through safety. However, the difference between the direct and total effects 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.

[32] The elasticity could be smaller if increased generation time allows for built-up expertise. On the other hand, the elasticity could be larger if there is fatigue, for instance, of employees as generation time increases.

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

[34] Block-bootstrapped standard errors (clustered at the plant level) that account for the correlation between effect on generation and the effect on safety are 0.09 for initiating events and 0.30 for fires.

[35] Robustness checks to account for differential historical usage give similar results. For instance, I can include cumulative lifetime generation as an exogenous variable (excluding current generation, which is subject to simultaneity); this conditions on relative plant usage. As shown in Appendix 2, results for the divestiture coefficient are nearly identical. Rather than using cumulative generation, several lags of generation can be included as right-hand side variables. As shown in Appendix 2, this gives similar results. The coefficient on divestiture is somewhat smaller in absolute value, but is not statistically different from the main results.

4.3.2 Calculating 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 be 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 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.[36] Then for total effect of divestiture on generation of 10 percent, the direct effect after accounting for both fires and initiating events is calculated to be 9 percent.[37] This is very close to the total effect of 10 percent, because unsafe events occur fairly infrequently.

4.4 Robustness Checks

Several robustness checks give very similar results (table 4). First, I estimate a conditional negative binomial with fixed effects specification in columns (1), (4), and (7).[38] For this specification, the individual effects α_i enter the conditional negative binomial specification only in the variance parameter. That is, this specification does not allow for heterogeneity in the mean across units (Allison and Waterman 2002). Next, columns (2), (5), and (8) give results for a Poisson specification. All point estimates and standard errors are very similar to the results given by the unconditional negative binomial model. Finally, I show OLS specifications in columns (3), (6), and (9). To compare the magnitude in the OLS specifications with the magnitude in the count specifications, I show the percentage change in the expected number of counts attributable to divestiture for all regressions. Overall, the results are stable to various assumptions on functional form. For all future regressions using the three count variables, I show results for the unconditional negative binomial specification.

[36] I examined daily generation data and descriptions (from Davis and Wolfram 2012) 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.

[37] The block-bootstrapped standard error (clustered at the plant level) that accounts for the correlation between effect on generation and the effect on safety is 0.02.

[38] The fixed-effects conditional 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.

I also examine whether the results are driven by outliers. I perform a jackknife procedure both at the plant level and the year level. As shown in Appendix 2, the results are stable to dropping any one plant or any one year. Additionally, I show that the results are not driven by the company (Exelon) with the greatest number (17) of divested reactors. Results in Appendix 2 when Exelon reactors are dropped are very similar to the main results, with the exception of the worker radiation exposure measures.

4.5 Heterogeneity

I next explore whether heterogeneity can also be observed across reactor fixed characteristics (table 5). I first divide reactors according to type (BWR versus PWR). Since BWR reactors were more likely to divested, one might worry about either bias from selection or about external validity. With the exception of the worker radiation exposure equations (columns 4 and 5), the coefficient on divestiture is not statistically different for BWR versus PWR reactors. I next divide reactors by age, defining newer reactors (51 of 103) as those entering commercial operations in 1979 or later. Finally, I divide by design capacity, defining large reactors (49 of 103) as those with current capacity of at least 1000 MW. Age and size are not correlated with divestiture (table 2), but heterogeneity in the effect of divestiture does appear. There is some evidence that newer and larger reactors improved more, particularly for initiating events and escalated enforcement. The size and age definitions are highly correlated: the majority of newer reactors are large, and the majority of older reactors are small. As such, there is unfortunately insufficient power to separately test the effects of size and age. All heterogeneity results (in Appendix 2) are similar when the dependent variable is normalized by capacity factor.

4.6 State-Level Selection

Next 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, Vermont, 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. For all four specifications (table 6), the results are robust. The coefficient on divestiture is almost always negative, and the magnitudes are largely unchanged from the main specification. One exception is collective worker radiation exposure, which is sensitive to excluding the Northeast.[39]

4.7 Spillovers and Consolidation

Previous work has shown spillovers of safety practices across plants, including to the companies operating non-divested plants (MIT 2003, Rees 1994). 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. As described in section 2.2, INPO in particular has had substantial impact on the industry by facilitating best-practices sharing across all reactors in the U.S. (Rees 1994). 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 possible to test for these spillovers across all plants using this paper's empirical strategy. 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, such as more stringent NRC regulations. In Appendix 2, results are given for a test of intra-firm spillovers between divested and non-divested plants. I generally do not find an effect, with the exception of escalated enforcement, which falls at non-divested plants owned by companies that also own plants in regulated environments. One possible explanation is that operators fear scrutiny at all of their plants if an escalated enforcement action is taken at one plant. Although no evidence of intra-firm spillovers is found, it is possible there are nation-wide spillovers, biasing the main results. Finally, I also test for a consolidation effect, measured as the number of reactors owned by a plant's parent company, but generally fail to find an effect.

[39] As described in section 2.1, another selection concern relates to the timing of divestiture. If, for instance, plants that expected to have larger gains following divestiture were sold first, my results would be weighted in favor of those plants. In Appendix 2, I examine the robustness of the main results to including only four years of post-divestiture data at each of the plants. Results are noisy but similar to results including all years of data. Additionally, I examine the robustness of the results to using deregulation dates rather than divestiture dates. It is not clear what date to use, and related papers have used several measures of deregulation dates (Fabrizio, Rose, and Wolfram 2007, Craig and Savage 2009). Appendix 2 shows results for four different measures of deregulation, all of which will introduce measurement error. Results are generally robust to these alternative dates, with the exception of initiating events.

4.8 Dynamic Effects

There is some evidence that the benefits of divestiture would increase over time, both because some plant modifications would take time, and because the companies would learn. The event study graph (figure 1) showed 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, with results in table 7.[40] This specification also allows me to look for differential trends prior to divestiture. The coefficients on the linear trends are scaled to represent a three-year change. The pre-divestiture trend is generally very small, indicating that the plants were on similar trajectories.[41] Overall, trends post-divestiture are negative, consistent with learning. These downward trends are reassuring that the results are not driven by temporary changes following divestiture.

5 Conclusion

This paper provides empirical evidence on the effects of divestiture on nuclear power plant safety in the United States. I examine both the total effect of divestiture on safety and the effect when controlling for increased generation levels. The total effect is composed of both the direct effect on safety and an indirect effect. The latter arises from the fact that generation increased following divestiture, and thus plants may have experienced an increase in exposure to unsafe events. The total drop in safety incidents is estimated to be 17 percent for initiating events, 46 percent for fires, and 35 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. Worker radiation exposure, measured either collectively or on average, also decreases. When controlling for generation increases, I find that the direct effect on safety is more negative and more statistically significant. For a given capacity factor, the drop in safety incidents is estimated to be 28 percent for initiating events, 54 percent for fires, and 42 percent for escalated enforcement. Results are also larger, although imprecisely estimated, for worker radiation exposure.

The results are similar for a number of robustness checks, including concerns about selections on technology and location, the inclusion of pre-treatment trends, and jackknife procedures. In extensions, I find some heterogeneity, with larger results for newer, bigger reactors. I do not find evidence of spillovers or consolidation. However, it is likely that

[40] Ideally, one would estimate a full event study for all empirical specifications. However, for these infrequent events the results are extremely noisy. The coefficients are given in Appendix 2.

[41] One exception is escalated enforcement, which shows an upward trend prior to divestiture: the plants that were eventually sold off were worsening their safety records.

spillovers in the form of best-practices sharing exist, implying that deregulation had a larger effect than the results given above. Finally, a specification allowing for differential trends indicates that the effect has grown larger over time, providing reassurance that the results are not driven by temporary changes.

Several caveats apply. First, as described in section 3.1, the available information on power plant safety does not directly measure the risk of catastrophic failure. The measures analyzed are, however, widely used as indicators of power plant safety. A related concern about the data used is that the incentive alignment described applies only when maintenance for safety is positively correlated with a plant's ability to generate. This concern is mitigated as long as the NRC can force a plant to close. A third concern, then, is the possibility of either incomplete NRC enforcement or regulatory capture. Also, there is the possibility of end-of-life problems when plants close: if the plant operator can no longer earn a future stream of operating profits, it may choose to forgo safety-related repairs. Finally, it should be noted that the estimates in this paper are for the effect of the treatment on the treated units. That is, if plants that were never deregulated are dissimilar in time-invariant ways from the regulated plants, it is possible they would respond to divestiture differently.

Overall, this paper speaks to a number of timely issues, including the changing structure of the electricity industry and the incentives for safety at nuclear power plants. Although intuition is given throughout this paper for some of the mechanisms at work, theoretical predictions of the effect of deregulation on plant safety are not possible. As such, an empirical analysis of the effect is the best evidence available. While the infrequency of unsafe events at nuclear plants makes precise statistical estimates difficult, the results match anecdotal evidence. Deregulation of electricity markets led to increased operating efficiency, and it did not come at the cost of plant safety.

References

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

[2] Ando, Amy W. and Karen L. Palmer. 1998. "Getting on the Map: The Political Economy of State-Level Electricity Restructuring." RFF Discussion Paper 98-19-REV.

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

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

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

[6] Borenstein, Severin, James B. Bushnell, and Frank A. Wolak. 2002. "Measuring Market Inefficiencies in California's Restructured Wholesale Electricity Market." *American Economic Review* 92(5): 1376-1405.

[7] Bushnell, James B., Erin T. Mansur, and Celeste Saravia. 2009. "Vertical Arrangements, Market Structure, and Competition: An Analysis of Restructured US Electricity Markets." *American Economic Review* 98(1): 237-266.

[8] Bushnell, James B. and Catherine Wolfram. 2005. "Ownership Change, Incentives and Plant Efficiency: The Divestiture of U.S. Electric Generation Plants." CSEM Working Paper 140.

[9] Craig, J. Dean and Savage, Scott J. 2009. "Market Restructuring, Competition and the Efficiency of Electricity Generation: Plant-level Evidence from the United States 1996 to 2006." University of Colorado at Boulder Department of Economics Working Paper No. 09-06. Accessed from http://dirwww.colorado.edu/Economics/papers/Wps-09/wp09-06/wp09-06.pdf.

[10] 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.

[11] Davis, Lucas W. 2012. "Prospects for U.S. Nuclear Power." *Journal of Economic Perspectives* 26(1): 49-66.

[12] Davis, Lucas W. and Catherine Wolfram. 2012. "Deregulation, Consolidation, and Efficiency: Evidence from U.S. Nuclear Power." *American Economic Journal: Applied Economics* 4(4): 194-225.

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

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

[15] 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.

[16] 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.

[17] Fowlie, Meredith. 2010. "Emissions Trading, Electricity Restructuring, and Investment in Pollution Abatement." *American Economic Review* 100(3): 837-869.

[18] 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.

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

[20] 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.

[21] 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.

[22] 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.

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

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

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

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

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

[28] Mansur, Erin T. 2008. "Measuring Welfare in Restructured Electricity Markets." *Review of Economics and Statistics* 90(2): 369–386.

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

[30] Massachusetts Institute of Technology (MIT). 2009. "Update of the MIT 2003 Future of Nuclear Power: An Interdisciplinary MIT Study." MIT Energy Initiative.

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

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

[33] Rees, Joseph V. 1994. *Hostages of Each Other: The Transformation of Nuclear Safety since Three Mile Island*. Chicago: University of Chicago Press.

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

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

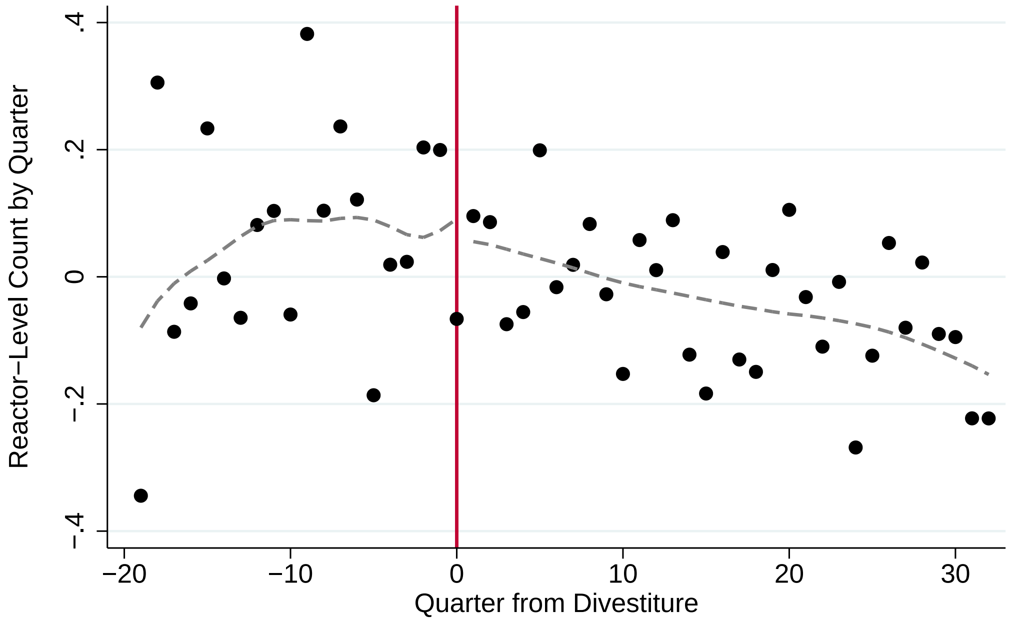
[36] Rust, John and Geoffrey Rothwell. 1995. "Optimal Response to a Shift in Regulatory Regime: the Case of the US Nuclear Power Industry." *Journal of Applied Econometrics* 10(S1): S75-S118.

[37] 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.

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

[39] 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 Unsafe Events, Quarterly Event Study



Notes: This figure plots unsafe events at divested units relative to non−divested units. Time is normalized relative to divestiture. Unsafe events include initiating events, fires, and escalated enforcement. The median divestiture is in 2001. Quarter−of−sample effects have been removed. Dashed grey lines show a lowess smoother in the pre−period and post−period.

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 (person-rems)	116.04	89.95	1.40	893.01
Average worker radiation exposure (rems)	0.15	0.06	0.01	0.47
Escalated enforcement	0.44	0.75	0	6
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: Data are for 103 nuclear power reactors operating in the U.S. from 1996-2009. Both radiation exposure variables are measured at the plant level. For collective exposure, the numbers in this table are a simple mean across units within the plant. Some plants (e.g., Browns Ferry) are dropped from the sample because radiation exposure measurements include closed units. Also, data on these variables is only available through 2008. Capacity factor is defined as generation divided by design capacity. 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 changes to reactor capacity over time (uprates). N = 1442 for count variables and reliability measures, 1259 for radiation variables.

Table 2: Comparing Divested and Non-Divested Nuclear Reactors

	never divested	later divested	t-stat	p-value
A. Safety measures:				
Initiating events	1.05	0.92	0.93	0.36
Fires	0.085	0.056	0.82	0.41
Collective worker radiation exposure (person-rems)	148.38	163.73	-0.84	0.41
Average worker radiation exposure (rems)	0.18	0.19	-0.63	0.53
Escalated enforcement	0.75	0.98	-1.54	0.13
B. Reliability measures:				
Net generation (million MWh)	6.90	5.67	2.17	0.03
Capacity factor	0.82	0.70	2.59	0.01

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. For collective exposure, the numbers in this table are a simple mean across units within the plant. Some plants (e.g., Browns Ferry) are dropped from the sample because radiation exposure measurements include closed units. For the count variables and reliability measures, (measured by reactor), N = 165 for never divested units, 144 for later divested units. For the radiation exposure variables (measured plant), N = 95 for never divested plants, 87 for later divested plants. One reactor (Watts Bar 1) starts commercial operation during this time. T-tests are clustered at the plant level.

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

	(1)	(2)	(3)	(4)	(5)
Dependent variable:	Initiating Events	Fires	Escalated Enforcement	Collective Worker Radiation Exposure (person-rems)	Average Worker Radiation Exposure (rems)
A: Dependent variable is not normalized					
Divestiture	-0.192	-0.622	-0.426*	-42.2	-0.025
	(0.130)	(0.433)	(0.247)	(67.3)	(0.022)
Change in expected value	-17%	-46%	-35%	-25%	-18%
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2245	1950	1442	1749	1749
B: Dependent variable is normalized by capacity factor					
Divestiture	-0.335***	-0.767*	-0.552**	-180.2	-0.108
	(0.122)	(0.440)	(0.277)	(278.3)	(0.103)
Change in expected value	-28%	-54%	-42%	-93%	-69%
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2207	1925	1425	1729	1729

Notes: Observation is a commercial nuclear power reactor (U.S.) in a year 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. Normalization for the count regressions is accomplished by including capacity factor as an independent variable with coefficient constrained to unity. In columns (1), (2), and (3), the percentage change in expected value is equal to exp(coefficient) minus one; for columns (4) and (5), it is equal to the coefficient divided by the sample average at non-divested reactors. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009; and radiation exposure is 1974-2008. For fires and escalated enforcement, some reactors (34 and 2, respectively) are dropped because all observations are zero. Additionally, some observations have zero capacity factor and are dropped in panel B. Standard errors are clustered by plant. Stars (*, **, and ***) 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)
Dependent variable:	Initiating Events			Fires			Escalated Enforcement		
	A: Dependent variable is not normalized								
Divestiture	-0.21	-0.18	-0.19	-0.60	-0.62	-0.04	-0.41	-0.43*	-0.22*
	(0.13)	(0.13)	(0.13)	(0.45)	(0.43)	(0.03)	(0.26)	(0.25)	(0.12)
Change in expected value	-19%	-16%	-15%	-45%	-46%	-48%	-34%	-35%	-56%
Specification	CNB	Poisson	OLS	CNB	Poisson	OLS	CNB	Poisson	OLS
Year effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	2245	2245	2245	1950	1950	1950	1442	1442	1442
	B: Dependent variable is normalized by capacity factor								
Divestiture	-0.34***	-0.32**	-0.54**	-0.74	-0.77*	-0.07	-0.53*	-0.55**	-0.37
	(0.12)	(0.12)	(0.23)	(0.46)	(0.44)	(0.05)	(0.28)	(0.28)	(0.31)
Change in expected value	-29%	-27%	-31%	-52%	-54%	-68%	-41%	-42%	-67%
Specification	CNB	Poisson	OLS	CNB	Poisson	OLS	CNB	Poisson	OLS
Year effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	2207	2207	2207	1925	1925	1925	1425	1425	1425

Notes: Observation is a commercial nuclear power plant (U.S.) in a year. 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. CNB is a conditional negative binomial; OLS is ordinary least squares. Results are nearly identical with an unconditional negative binomial with constant dispersion parameterization. Normalization for the count regressions is accomplished by including capacity factor as an independent variable with coefficient constrained to unity. 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 reactors (34 and 2, respectively) are dropped in the count regressions because all observations are zero. Additionally, some observations have zero capacity factor and are dropped in panel B. Standard errors are clustered by plant. Stars (*, **, and ***) denote 10%, 5%, and 1% significance.

Table 5: Heterogeneity by Reactor Characteristics

Dependent variable:	(1) Initiating Events	(2) Fires	(3) Escalated Enforcement	(4) Collective Worker Radiation Exposure (person-rems)	(5) Average Worker Radiation Exposure (rems)
			Dependent variable is not normalized		
Divestiture, BWR	-0.13	-0.57	-0.44	-166.5*	-0.065**
	(0.13)	(0.52)	(0.30)	(87.5)	(0.029)
Divestiture, PWR	-0.26	-0.70	-0.41	109.9**	0.024
	(0.20)	(0.62)	(0.31)	(48.8)	(0.022)
Chi-squared stat	0.41	0.03	0.01	12.13***	6.81**
Divestiture, older reactors	-0.01	-0.29	-0.22	-78.3	-0.045
	(0.15)	(0.44)	(0.25)	(89.7)	(0.028)
Divestiture, newer reactors	-0.40**	-1.14	-0.76**	14.5	0.006
	(0.18)	(0.68)	(0.33)	(47.7)	(0.021)
Chi-squared stat	4.01**	1.50	3.44*	1.42	2.95*
Divestiture, small reactors	0.02	-0.61	-0.27	-54.2	-0.060*
	(0.15)	(0.51)	(0.24)	(91.3)	(0.030)
Divestiture, large reactors	-0.41**	-0.63	-0.64*	-29.4	0.012
	(0.16)	(0.61)	(0.35)	(75.7)	(0.021)
Chi-squared stat	5.16**	<0.01	1.52	0.06	4.82*
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2245	1950	1442	1749	1749

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 year 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 1974-2008. For fires and escalated enforcement, some reactors (34 and 2, respectively) are dropped in the count regressions because of all zero outcomes. Standard errors are clustered by plant. Stars (*, **, and ***) denote 10%, 5%, and 1% significance.

Table 6: State-Level Selection

Dependent variable: Divestiture	(1) Initiating Events	(2) Fires	(3) Escalated Enforcement	(4) Collective Worker Radiation Exposure (person-rems)	(5) Average Worker Radiation Exposure (rems)
	A. Dependent variable is not normalized				
Excluding Michigan	-0.16	-0.63	-0.42*	-32.9	-0.020
	(0.13)	(0.44)	(0.25)	(69.3)	(0.022)
Excluding California	-0.20	-0.63	-0.44*	-43.0	-0.025
	(0.13)	(0.44)	(0.25)	(68.2)	(0.022)
Excluding Iowa, Vermont, and Wisconsin	-0.21	-0.73*	-0.48*	-50.0	-0.030
	(0.13)	(0.44)	(0.26)	(70.8)	(0.023)
Excluding Northeast	-0.33*	-1.05*	-0.33	16.4	-0.017
	(0.19)	(0.63)	(0.29)	(73.8)	(0.040)
	B: Dependent variable is normalized by capacity factor				
Excluding Michigan	-0.31**	-0.77*	-0.56*	-192.4	-0.143
	(0.12)	(0.45)	(0.29)	(292.9)	(0.108)
Excluding California	-0.34***	-0.77*	-0.56**	-178.5	-0.106
	(0.12)	(0.45)	(0.28)	(281.3)	(0.105)
Excluding Iowa, Vermont, and Wisconsin	-0.36***	-0.89**	-0.63**	-210.3	-0.126
	(0.12)	(0.45)	(0.30)	(294.6)	(0.108)
Excluding Northeast	-0.48***	-1.28*	-0.47	44.7	-0.082
	(0.18)	(0.68)	(0.31)	(165.1)	(0.069)

Notes: Each coefficient is from a separate regression (eight per outcome variable). Observation is a commercial nuclear power reactor (U.S.) in a year 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. Columns (1), (2), and (3) are negative binomial specifications with year and reactor effects. Columns (4) and (5) are OLS specifications with year and facility effects. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009; and radiation exposure is 1974-2008. For fires and escalated enforcement, some reactors (34 and 2, respectively) are dropped in the count regressions because of all zero outcomes. Additionally, some observations have zero capacity factor and are dropped in panel B. Standard errors are clustered by plant. Stars (*, **, and ***) denote 10%, 5%, and 1% significance.

Table 7: Learning

	(1)	(2)	(3)	(4)	(5)
Dependent variable:	Initiating Events	Fires	Escalated Enforcement	Collective Worker Radiation Exposure (person-rems)	Average Worker Radiation Exposure (rems)
A: Dependent variable is not normalized					
Divestiture	-0.01	-0.01	-0.43	-38.7	0.030
	(0.18)	(0.68)	(0.32)	(42.2)	(0.025)
Linear trend pre-divestiture	-0.01	-0.06	0.35**	16.4	-0.013
	(0.04)	(0.16)	(0.15)	(24.5)	(0.011)
Linear trend post-divestiture	-0.14	-0.38	-0.29*	-46.5*	-0.016
	(0.12)	(0.35)	(0.17)	(26.3)	(0.010)
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2245	1950	1442	1749	1749
B. Dependent variable is normalized by capacity factor					
Divestiture	-0.14	-0.07	-0.41	20.5	0.277
	(0.17)	(0.68)	(0.35)	(227.7)	(0.254)
Linear trend pre-divestiture	0.01	-0.07	0.27*	-26.6	-0.119
	(0.04)	(0.16)	(0.16)	(100.1)	(0.088)
Linear trend post-divestiture	-0.19	-0.42	-0.35**	-108.8	-0.025
	(0.12)	(0.35)	(0.17)	(106.3)	(0.050)
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2207	1925	1425	1729	1729

Notes: Learning variable has been scaled to represent a three-year change. Observation is a commercial nuclear power reactor (U.S.) in a year 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. Normalization for the count regressions is accomplished by including capacity factor as an independent variable with coefficient constrained to unity. Samples dates vary by variable. Initiating events are 1988-2009; fires are 1991-2009; escalated enforcement is 1996-2009; and radiation exposure is 1974-2008. For fires and escalated enforcement, some reactors (34 and 2, respectively) are dropped in the count regressions because of all zero outcomes. Additionally, some observations have zero capacity factor and are dropped in panel B. Standard errors are clustered by plant. Stars (*, **, and ***) denote 10%, 5%, and 1% significance.

Appendix 1: Model

I model profit maximization of a nuclear power plant in a competitive generation market, then I derive implications for expenditures on reliability and safety maintenance.

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.[42] Second, assume that $p > c^o$; the market price is higher than the nuclear plant's variable costs.[43]

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.[44] 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, $r''(a) > 0$:

[42] 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.

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

[44] 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.

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 maximization problem is[45]

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

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),[46] 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

[45] 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.

[46] 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.

the cost of an unplanned outage.

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.[47]

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).[48] 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.

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

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

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 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; the Hessian matrix is:

$$\begin{bmatrix} -r''(a^r) \cdot \pi - r''(a^r) \cdot c^u - \frac{\partial^2 c^r(a^r, \pi)}{\partial^2 a^r} & 0 \\ 0 & -s''(a^s) \cdot \theta \cdot c^s - \frac{\partial^2 c^s(a^s, \pi)}{\partial^2 a^s} \end{bmatrix} \tag{10}$$

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

Comparative statics for the firm are:

$$\begin{bmatrix} \frac{\partial a^r}{\partial \pi} & \frac{\partial a^r}{\partial c^u} & \frac{\partial a^r}{\partial \theta} \\ \frac{\partial a^s}{\partial \pi} & \frac{\partial a^s}{\partial c^u} & \frac{\partial a^s}{\partial \theta} \end{bmatrix} = -Hessian^{-1} \cdot \begin{bmatrix} \frac{\partial FOC_1}{\partial \pi} & \frac{\partial FOC_1}{\partial c^u} & \frac{\partial FOC_1}{\partial \theta} \\ \frac{\partial FOC_2}{\partial \pi} & \frac{\partial FOC_2}{\partial c^u} & \frac{\partial FOC_2}{\partial \theta} \end{bmatrix} \tag{11}$$

$$\begin{aligned} &= -\begin{bmatrix} -r''(a^r)\cdot\pi - r''(a^r)\cdot c^u - \frac{\partial^2 c^r(a^r,\pi)}{\partial^2 a^r} & 0 \\ 0 & -s''(a^s)\cdot c^s - \frac{\partial^2 c^s(a^s,\pi)}{\partial^2 a^s} \end{bmatrix}^{-1} \\ &\quad \cdot \begin{bmatrix} -r'(a^r) - \frac{\partial^2 c^r}{\partial a^r \partial \pi} & -r'(a^r) & 0 \\ -\frac{\partial^2 c^s}{\partial a^s \partial \pi} & 0 & -s'(a^s)\cdot c^s \end{bmatrix} \end{aligned} \tag{12}$$

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

$$= -\begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}^{-1} \begin{bmatrix} c & d & 0 \\ e & 0 & f \end{bmatrix} \tag{13}$$

$$= -\begin{bmatrix} \frac{1}{a} & 0 \\ 0 & \frac{1}{b} \end{bmatrix} \begin{bmatrix} c & d & 0 \\ e & 0 & f \end{bmatrix} \tag{14}$$

$$= -\begin{bmatrix} \frac{c}{a} & \frac{d}{a} & 0 \\ \frac{e}{b} & 0 & \frac{f}{b} \end{bmatrix} \tag{15}$$

$$= \begin{bmatrix} ind & + & 0 \\ - & 0 & + \end{bmatrix} \tag{16}$$

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 $\frac{\partial^2 c(a^s,\pi)}{\partial a^s \partial \pi} = 0$, then potential operating profits will not affect the optimal expenditures on safety maintenance.

Appendix 2: Additional Tables and Figures

Description

This appendix contains additional tables and figures, left out of the main paper for space considerations.

Tables

1. Additional outcome variables
2. Additional characteristics for comparing divested and non-divested nuclear reactors
3. Dropping if capacity factor < 0.01
4. Cumulative generation
5. Lagged capacity factor
6. Jackknife
7. Dropping Exelon
8. Heterogeneity, for normalized dependent variable
9. Robustness to endogenous timing of divestiture
10. Deregulation dates
11. Intra-firm spillovers
12. Consolidation
13. Event study coefficients

Appendix Table 1: Additional Outcome Variables

	(1)	(2)
Dependent variable:	Withholding Information	Retaliation
A: Dependent variable is not normalized		
Divestiture	-0.460	-1.436
	(1.167)	(0.993)
Specification	Neg Bin	Neg Bin
Year effects	Yes	Yes
Reactor effects	Yes	Yes
Plant effects	No	No
Number of observations	1442	1442
B: Dependent variable is normalized by capacity factor		
Divestiture	-0.658	-1.570
	(1.216)	(1.117)
Specification	Neg Bin	Neg Bin
Year effects	Yes	Yes
Reactor effects	Yes	Yes
Plant effects	No	No
Number of observations	1425	1425

Notes: 81 reactors had no withholding information violations, and 66 reactors had no worker retaliation violations. Data are from the NRC escalated enforcement actions dataset. Withholding Information violations are escalated enforcement actions whose short description refers to "failure to provide information," "withholding information," "violation of 10 CFR 50.9," "lack of complete and accurate information," etc. Worker Retaliation violations are from actions refering to "safety culture," "harassment," "retaliation," "SWCE," "violation of 10 CFR 50.7," etc.

Appendix Table 2: Additional Characteristics for Comparing Divested and Non-Divested Reactors

	never divested	later divested	t-stat	p-value
C. Reactor characteristics:				
Percent PWR	0.78	0.54	1.99	0.05
Age in 1998	18.36	18.80	-0.27	0.79
Capacity (MWe)	959.67	921.92	0.67	0.50
Number of operating reactors at plant	1.87	1.71	1.11	0.27
Manufacturer:				
Babcock & Wilcox	0.09	0.04	0.78	0.44
Combustion Engineering	0.18	0.08	1.15	0.25
General Electric	0.22	0.46	-1.99	0.05
Westinghouse	0.51	0.42	0.71	0.48
Location:				
West	0.15	0.00	2.13	0.04
Midwest	0.18	0.38	-1.68	0.10
South	0.67	0.13	5.02	<0.01
Northeast	0.00	0.50	-5.52	<0.01
D. Maximum generating capacity:				
Licensed capacity	101.94	101.23	1.30	0.20

Notes: For maximum generating capacity (measured annually at reactors), N = 165 for never divested units, 144 for later divested units. For the fixed characteristics, N = 55 for never divested plants, 48 for later divested plants. One reactor (Watts Bar 1) starts commercial operation during this time. T-tests are clustered at the plant level.

Appendix Table 3: Dropping if Capacity Factor <0.01

	(1)	(2)	(3)	(4)	(5)
Dependent variable:	Initiating Events	Fires	Escalated Enforcement	Collective Worker Radiation Exposure (person-rems)	Average Worker Radiation Exposure (rems)
Divestiture	-0.205	-0.635	-0.419*	-32.8	-0.024
	(0.127)	(0.431)	(0.252)	(64.6)	(0.022)
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2207	1925	1425	1729	1729

Notes: Same regressions as in panel A of table 3, except observations with capacity factor < 0.01 have been dropped (so the sample is the same as for panel B of table 3).

Appendix Table 4: Cumulative Generation

	(1)	(2)	(3)	(4)	(5)
Dependent variable:	Initiating Events	Fires	Escalated Enforcement	Collective Worker Radiation Exposure (person-rems)	Average Worker Radiation Exposure (rems)
A: Dependent variable is not normalized					
Divestiture	-0.234*	-0.622	-0.417*	-52.7	-0.022
	(0.123)	(0.431)	(0.249)	(67.7)	(0.020)
Cumulative generation, million MWh	-0.011***	-0.0009	-0.020**	-0.857	0.0003
	(0.003)	(0.011)	(0.008)	(0.568)	(0.0002)
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2232	1948	1441	1686	1686
B: Dependent variable is normalized by capacity factor					
Divestiture	-0.362***	-0.766*	-0.538*	-226.1	-0.142
	(0.118)	(0.440)	(0.281)	(278.5)	(0.096)
Cumulative generation, million MWh	-0.008***	0.001	-0.017*	2.261	0.002*
	(0.003)	(0.011)	(0.009)	(2.957)	(0.001)
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2194	1923	1424	1666	1666

Appendix Table 5: Lagged Capacity Factor

Dependent variable:	(1) Initiating Events	(2) Fires	(3) Escalated Enforcement	(4) Collective Worker Radiation Exposure (person-rems)	(5) Average Worker Radiation Exposure (rems)
A: Dependent variable is not normalized					
Divestiture	-0.204*	-0.523	-0.213	-38.3	-0.030
	(0.123)	(0.462)	(0.245)	(72.3)	(0.021)
1st lag: Capacity factor	0.692***	0.527	-0.678	138.0	0.149***
	(0.167)	(0.674)	(0.521)	(127.1)	(0.033)
2nd lag: Capacity factor	-0.212	-0.599	-1.074***	-331.7***	-0.021
	(0.148)	(0.671)	(0.274)	(111.0)	(0.034)
3rd lag: Capacity factor	-0.097	-2.256***	0.003	-146.1*	0.006
	(0.192)	(0.568)	(0.287)	(83.4)	(0.028)
Number of observations	2093	1866	1393	1508	1508
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
B: Dependent variable is normalized by capacity factor					
Divestiture	-0.311**	-0.671	-0.338	-36.1	-0.086
	(0.122)	(0.471)	(0.245)	(258.0)	(0.091)
1st lag: Capacity factor	0.512***	0.581	0.022	-897.2	-0.167
	(0.181)	(0.729)	(0.532)	(1098.1)	(0.529)
2nd lag: Capacity factor	-0.401***	-0.722	-1.287***	-2801.3**	-0.854**
	(0.141)	(0.718)	(0.266)	(1069.0)	(0.322)
3rd lag: Capacity factor	-0.166	2.249***	-0.085	-540.1	-0.113
	(0.187)	(0.564)	(0.286)	(461.0)	(0.162)
Number of observations	2074	1851	1382	1493	1493
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes

Appendix Table 6: Jackknife Regressions

A. Jackknife Regressions, by Plant

A1. Dependent variable not normalized

Variable	Obs	Mean	Min	Max
initiating events	66	-0.192	-0.225	-0.139
fires	66	-0.622	-0.760	-0.494
escalated enforcement	66	-0.426	-0.491	-0.312
collective worker radiation exposure	66	-42.2	-68.4	-10.7
average worker radiation exposure	66	-0.025	-0.032	-0.014

A2. Dependent variable normalized

Variable	Obs	Mean	Min	Max
initiating events	66	-0.335	-0.366	-0.286
fires	66	-0.767	-0.912	-0.644
escalated enforcement	66	-0.552	-0.634	-0.399
collective worker radiation exposure	66	-180.2	-274.9	35.8
average worker radiation exposure	66	-0.108	-0.151	-0.028

B. Jackknife Regressions, by Year

B1. Dependent variable not normalized

Variable	Obs	Mean	Min	Max
initiating events	22	-0.192	-0.233	-0.102
fires	19	-0.623	-0.864	-0.474
escalated enforcement	14	-0.426	-0.595	-0.327
collective worker radiation exposure	35	-42.3	-51.5	-23.6
average worker radiation exposure	35	-0.025	-0.029	-0.021

B2. Dependent variable normalized

Variable	Obs	Mean	Min	Max
initiating events	22	-0.335	-0.378	-0.241
fires	19	-0.768	-1.023	-0.611
escalated enforcement	14	-0.552	-0.721	-0.421
collective worker radiation exposure	35	-180.3	-276.4	-57.5
average worker radiation exposure	35	-0.108	-0.144	-0.053

Notes: Same regressions as in table 3, except a jackknife procedure has been performed. For panel A, the jackknife was by plant. For panel B, the jackknife was by year.

Appendix Table 7: Dropping Exelon

Dependent variable:	(1) Initiating Events	(2) Fires	(3) Escalated Enforcement	(4) Collective Worker Radiation Exposure (person-rems)	(5) Average Worker Radiation Exposure (rems)
	A: Dependent variable is not normalized				
Divestiture	-0.217	-0.396	-0.395	32.2	-0.006
	(0.162)	(0.527)	(0.315)	(73.5)	(0.024)
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	1873	1627	1204	1534	1534
	B: Dependent variable is normalized by capacity factor				
Divestiture	-0.351**	-0.512	-0.524	190.6	-0.00003
	(0.155)	(0.520)	(0.371)	(178.2)	(0.062)
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	1842	1607	1192	1518	1518

Notes: Same regression as in table 3, except dropping all seventeen reactors eventually acquired by Exelon.

Appendix Table 8: Heterogeneity by Reactor Characteristics

	(1)	(2)	(3)	(4)	(5)
Dependent variable:	Initiating Events	Fires	Escalated Enforcement	Collective Worker Radiation Exposure (person-rems)	Average Worker Radiation Exposure (rems)
Dependent variable is normalized by capacity factor					
Divestiture, BWR	-0.29**	-0.71	-0.55*	-523.3	-0.185
	(0.14)	(0.53)	(0.33)	(425.6)	(0.180)
Divestiture, PWR	-0.39**	-0.87	-0.56	236.9	-0.014
	(0.18)	(0.59)	(0.37)	(157.9)	(0.069)
Chi-squared stat	0.23	0.05	<0.01	3.50*	0.74
Divestiture, older reactors	-0.21	-0.46	-0.37	-320.3	-0.172
	(0.14)	(0.44)	(0.29)	(385.8)	(0.143)
Divestiture, newer reactors	-0.48***	-1.27*	-0.86**	40.7	-0.007
	(0.17)	(0.71)	(0.37)	(134.4)	(0.060)
Chi-squared stat	2.08	1.27	2.25	1.35	1.89
Divestiture, small reactors	-0.17	-0.80	-0.46	-306.7	-0.211
	(0.15)	(0.51)	(0.28)	(435.4)	(0.167)
Divestiture, large reactors	-0.51***	-0.72	-0.68*	-45.0	0.003
	(0.16)	(0.63)	(0.38)	(216.9)	(0.059)
Chi-squared stat	3.25*	0.01	0.40	0.38	1.92
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2207	1925	1425	1729	1729

Notes: Same regression as table 5 in the paper, except the dependent variable is normalized by capacity factor.

Appendix Table 9: Robustness to Endogenous Timing:
Cutting Window off at 4-Years Post-treatment, with Learning

Dependent variable:	(1) Initiating Events	(2) Fires	(3) Escalated Enforcement	(4) Collective Worker Radiation Exposure (person-rems)	(5) Average Worker Radiation Exposure (rems)
	A: Dependent variable is not normalized				
Divestiture	0.01	-0.31	-0.16	-63.2	0.026
	(0.21)	(0.92)	(0.43)	(46.3)	(0.027)
Linear trend pre-divestiture	-0.004	-0.07	0.33**	17.6	-0.012
	(0.04)	(0.17)	(0.15)	(24.4)	(0.011)
Linear trend post-divestiture	-0.14	-0.02	-0.73*	-6.5	-0.010
	(0.19)	(0.97)	(0.41)	(25.5)	(0.011)
Specification	Poisson	Poisson	Poisson	OLS	OLS
Year effects	Y	Y	Y	Y	Y
Reactor effects	Y	Y	Y	N	N
Plant effects	N	N	N	Y	Y
Number of observations	2084	1789	1281	1677	1677
	B. Dependent variable is normalized by capacity factor				
Divestiture	-0.11	-0.40	-0.15	-46.9	0.248
	(0.19)	(0.93)	(0.47)	(227.5)	(0.244)
Linear trend pre-divestiture	0.02	-0.08	0.25	-23.8	-0.119
	(0.04)	(0.17)	(0.16)	(100.3)	(0.089)
Linear trend post-divestiture	-0.20	-0.05	-0.81*	0.857	0.022
	(0.19)	(0.96)	(0.42)	(112.3)	(0.069)
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2046	1764	1264	1657	1657

Notes: Same regressions as in table 7, except dropping observations after four years of divestiture. It is necessary to comapre to table 7 rather than table 3 (main results), because the treatment effect changes over time.

Appendix Table 10: Deregulation Dates

Dependent variable:	(1) Initiating Events	(2) Fires	(3) Escalated Enforcement	(4) Collective Worker Radiation Exposure (person-rems)	(5) Average Worker Radiation Exposure (rems)
A: Dependent variable is not normalized					
dereg_main	-0.006	-0.651*	0.017	-2.82	-0.005
	(0.122)	(0.377)	(0.249)	(77.9)	(0.028)
dereg_law	0.009	-0.480	-0.114	-69.9	-0.008
	(0.126)	(0.350)	(0.252)	(70.6)	(0.025)
dereg_retail	-0.103	-0.414	-0.286	-45.7	0.009
	(0.133)	(0.415)	(0.272)	(66.8)	(0.023)
dereg_implement	0.020	-0.352	-0.298	-58.0	-0.004
	(0.108)	(0.348)	(0.268)	(63.4)	(0.023)
B: Dependent variable is normalized by capacity factor					
dereg_main	-0.123	-0.781**	-0.019	-163.9	-0.196
	(0.121)	(0.385)	(0.282)	(290.5)	(0.120)
dereg_law	-0.094	-0.576	-0.159	-245.6	-0.162
	(0.124)	(0.360)	(0.283)	(263.0)	(0.102)
dereg_retail	-0.228*	-0.502	-0.427	-302.9	-0.192
	(0.129)	(0.416)	(0.302)	(279.6)	(0.121)
dereg_implement	-0.094	-0.444	-0.437	-268.2	-0.173*
	(0.102)	(0.357)	(0.296)	(256.4)	(0.103)

Notes: Each dependent variable is for a separate regression (eight regressions total). Regressions are otherwise the same as in table 3. dereg_main: this variable turns on when legislation is first passed, but only in states where activities were never suspended. dereg_law turns on when legislation is first passed and turns off with when activities are suspended. dereg_retail turns on when retail choice begins and turns off when activities are suspended. dereg_implement turns on in the year Craig and Savage (2009) use for implementation, turns off when activities are suspended. Legislation, retail choice, and suspension dates are taken from the EIA's "Status of State Electric Industry Restructuring Activity" (February 2003), accessed October 2011 at http://www.eia.gov/cneaf/electricity/chg_str/restructure.pdf.

Appendix Table 11: Intra-Firm Spillovers

Dependent variable:	(1) Initiating Events	(2) Fires	(3) Escalated Enforcement	(4) Collective Worker Radiation Exposure (person-rems)	(5) Average Worker Radiation Exposure (rems)
A: Dependent variable is not normalized					
Divestiture	-0.22	-0.60	-0.56**	-72.4	-0.024
	(0.13)	(0.47)	(0.23)	(63.8)	(0.022)
Co-owned	-0.05	0.02	-0.80*	-144.3	-0.001
	(0.18)	(0.45)	(0.46)	(121.6)	(0.029)
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2245	1950	1442	1749	1749
B: Dependent variable is normalized by capacity factor					
Divestiture	-0.36***	-0.74	-0.68***	-187.9	-0.067
	(0.13)	(0.48)	(0.25)	(276.5)	(0.115)
Co-owned	-0.01	0.06	-0.72	-63.6	0.129
	(0.17)	(0.45)	(0.48)	(282.8)	(0.097)
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2207	1925	1425	1729	1729

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.

Appendix Table 12: Consolidation

	(1)	(2)	(3)	(4)	(5)
Dependent variable:	Initiating Events	Fires	Escalated Enforcement	Collective Worker Radiation Exposure (person-rems)	Average Worker Radiation Exposure (rems)
		A: Dependent variable is not normalized			
Divestiture	-0.29*	-0.21	-0.40	73.4	0.0002
	(0.16)	(0.56)	(0.33)	(68.4)	(0.027)
Consolidation	0.02	-0.07	-0.004	-23.4**	-0.005
	(0.02)	(0.06)	(0.03)	(10.9)	(0.005)
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2245	1950	1442	1749	1749
		B: Dependent variable is normalized by capacity factor			
Divestiture	-0.41***	-0.32	-0.54	203.3	-0.071
	(0.16)	(0.57)	(0.39)	(201.0)	(0.095)
Consolidation	0.01	-0.07	-0.001	-78.0	-0.007
	(0.02)	(0.07)	(0.04)	(53.0)	(0.030)
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2207	1925	1425	1729	1729

Notes: Consolidation is a count variable, equal to the number of other reactors owned by the parent company.

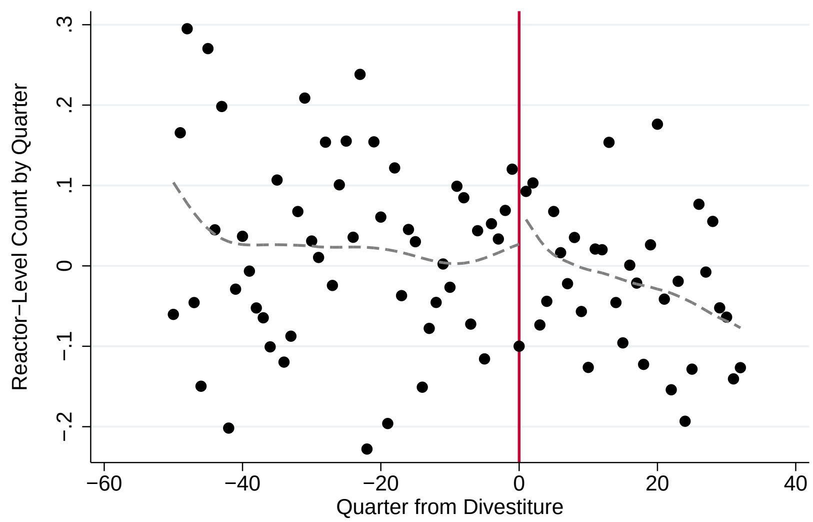
Appendix Table 13: Event Study

Dependent variable:	(1) Initiating Events	(2) Fires	(3) Escalated Enforcement	(4) Collective Worker Radiation Exposure (person-rems)	(5) Average Worker Radiation Exposure (rems)
	A: Dependent variable is not normalized				
>=5 years pre-divestiture	-0.018	0.561	-0.484	-9.94	0.023
	(0.156)	(0.792)	(0.444)	(76.46)	(0.028)
4 years pre-divestiture	-0.245	0.890	0.171	14.97	0.007
	(0.236)	(0.910)	(0.391)	(34.29)	(0.017)
3 years pre-divestiture	-0.219	0.957	-0.014	23.14	0.007
	(0.232)	(0.883)	(0.396)	(22.80)	(0.012)
2 years pre-divestiture	-0.020	-16.475***	0.443	16.83	0.004
	(0.198)	(0.746)	(0.391)	(45.37)	(0.019)
1 year pre-divestiture	normalized to zero	normalized to zero	normalized to zero	normalized to zero	normalized to zero
divestiture	0.058	0.318	0.302	-11.58	0.002
	(0.216)	(0.926)	(0.390)	(41.14)	(0.016)
1 year post-divestiture	-0.131	-0.035	-0.151	40.63	0.003
	(0.261)	(1.045)	(0.482)	(35.71)	(0.013)
2 years post-divestiture	-0.262	-0.091	-0.059	-0.76	0.013
	(0.245)	(1.066)	(0.423)	(34.03)	(0.017)
3 years post-divestiture	-0.167	-0.048	-0.672	-34.08	-0.001
	(0.222)	(1.022)	(0.588)	(29.27)	(0.018)
4 years post-divestiture	-0.184	0.184	-0.729	-44.38	-0.018
	(0.259)	(1.048)	(0.570)	(28.71)	(0.018)
>=5 years post-divestiture	-0.422*	-0.362	-0.518	-95.76*	-0.022
	(0.233)	(0.946)	(0.377)	(48.10)	(0.022)
Specification	Neg Bin	Neg Bin	Neg Bin	OLS	OLS
Year effects	Yes	Yes	Yes	Yes	Yes
Reactor effects	Yes	Yes	Yes	No	No
Plant effects	No	No	No	Yes	Yes
Number of observations	2245	1950	1442	1749	1749

Notes: There are no fires 2 years pre-divestiture at any plant.

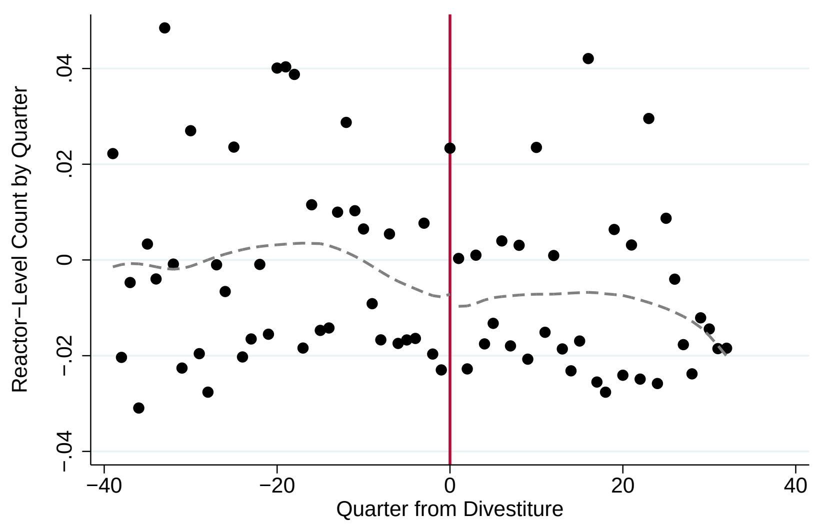
Figures

Figure A.1: Effect of Divestiture on Initiating Events, Quarterly Event Study



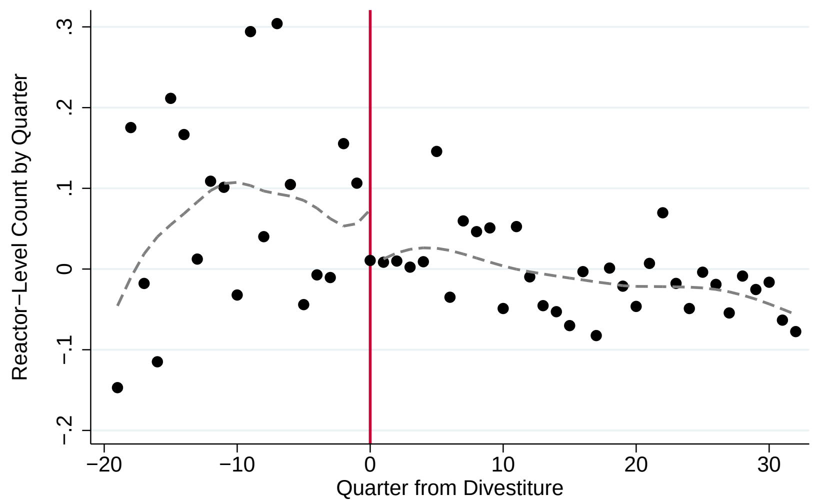
Notes: This figure plots initiating events at divested units relative to non−divested units. Time is normalized relative to divestiture. The median divestiture is in 2001. Quarter−of−sample effects have been removed. Dashed grey lines show a lowess smoother in the pre−period and post−period.

Figure A.2: Effect of Divestiture on Fires, Quarterly Event Study



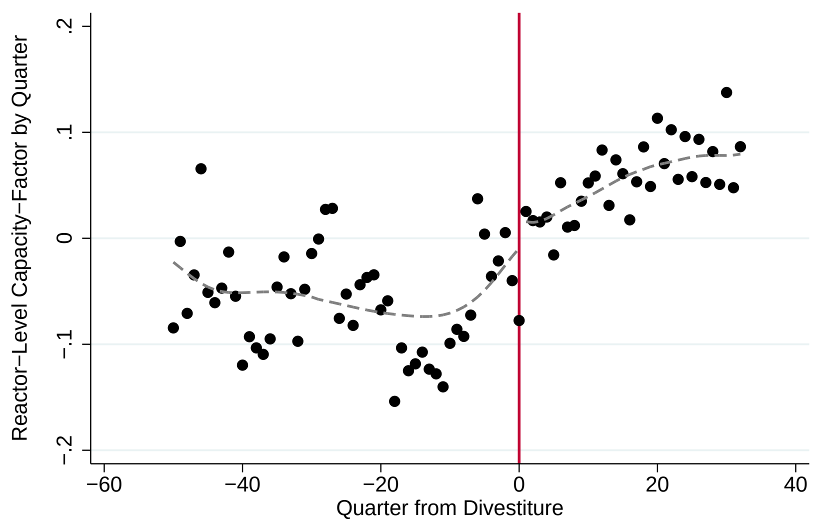
Notes: This figure plots fires at divested units relative to non−divested units. Time is normalized relative to divestiture. The median divestiture is in 2001. Quarter−of−sample effects have been removed. Dashed grey lines show a lowess smoother in the pre−period and post−period.

Figure A.3: Effect of Divestiture on Escalated Enforcement, Quarterly Event Study



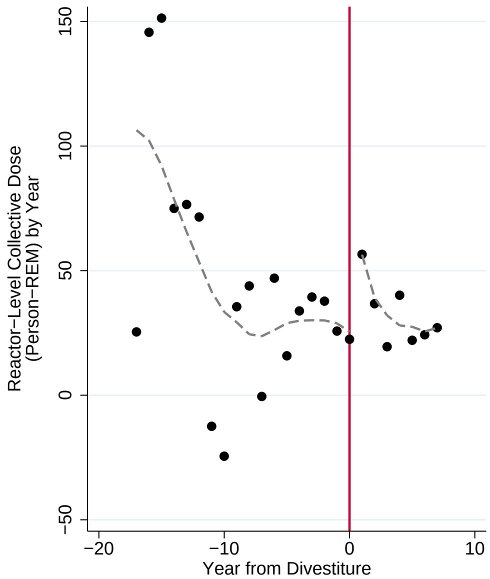
Notes: This figure plots escalated enforcement at divested units relative to non−divested units. Time is normalized relative to divestiture. The median divestiture is in 2001. Quarter−of−sample effects have been removed. Dashed grey lines show a lowess smoother in the pre−period and post−period.

Figure A.4: Effect of Divestiture on Generation, Quarterly Event Study

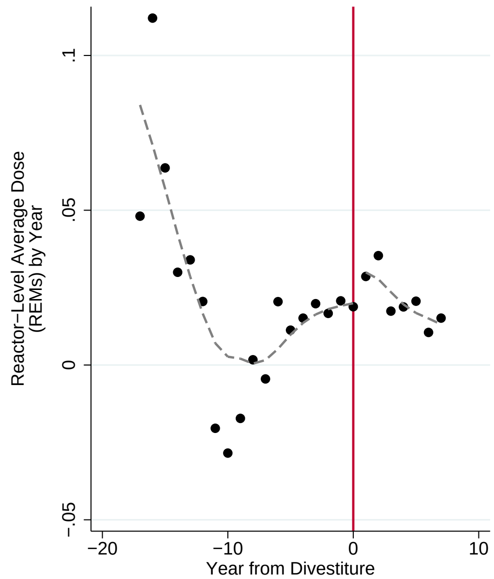


Notes: This figure plots capacity factor at divested units relative to non−divested units. Time is normalized relative to divestiture. The median divestiture is in 2001. Quarter−of−sample effects have been removed. Dashed grey lines show a lowess smoother in the pre−period and post−period.

Figure A.5: Effect of Divestiture on Worker Radiation Exposure, Annual Event Study



Notes: This figure plots collective worker radiation exposure (person−rems) at divested units relative to non−divested units. Time is normalized relative to divestiture. The median divestiture is in 2001. Year−of−sample effects have been removed. Dashed grey lines show a lowess smoother in the pre−period and post−period.



Notes: This figure plots average worker radiation exposure (rems) at divested units relative to non−divested units. Time is normalized relative to divestiture. The median divestiture is in 2001. Year−of−sample effects have been removed. Dashed grey lines show a lowess smoother in the pre−period and post−period.