Splitting the Uranium Triangle: the regulatory revolution and its impact on the safety of American nuclear power plants

Andrew G. Benson[a]

[a]*Sandia National Laboratories*[1]*, P.O. Box 5800, Albuquerque, NM, 87185-1108, USA*

Abstract

I present and analyze novel quantitative evidence on the evolution of the regulatory burden faced by the civilian nuclear power industry in the United States. Consistent with prior scholarship, my measures of regulatory burden exhibit an inflection point circa 1970, when new regulatory requirements proliferated and the time required to receive licenses to construct and operate reactors began to escalate. Beginning in the 1970s, ideologically liberal states exhibit a greater tendency to participate as an intervenor in federal proceedings for reactor licensing. I show that the degree of a state's intervention is statistically and substantively related to the time to receive a license. Lastly, I ask whether the licensing hold-up achieved its stated goal of increased reactor safety. Conditioning on observable technical characteristics, reactor age, and economic and political conditions during operation, reactors which took longer to receive an operating license exhibit a statistically lower rate of low-level safety incidents for which there are standardized reporting criteria. The size of the effect is such that a 1% increase in the time required to receive an operating license is associated with a 0.4% reduction in the expected monthly count of reported safety incidents.

Keywords:

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1. Introduction

The 1970s were a turbulent and contested era in the regulation of American nuclear power plants. The young environmental movement campaigned in opposition to nuclear power on matters of safety and sustainability, bringing these issues to the forefront of public concern (Barkan, 1979; Joppke, 1993). Consumer advocates disrupted the cozy relationship between regulated electric utilities and state public utility commissions through participation in proceedings and the development of new ideas and methods in energy planning, for the express purpose of dismantling the economic justification for nuclear power (Roe, 1984). State and local politicians propelled their careers with "not in my backyard" campaigns against proposed nuclear plants in or near their jurisdictions, making creative use of American federalism to intervene in a sector whose regulation the federal government had claimed exclusively for itself (Joppke, 1992; Wellock, 1998). The Atomic Energy Commission was split into two agencies, on the grounds that its duty to regulate safety should not be compromised by its promotional objectives (Walker and Wellock, 2010, p. 49). The once powerful Joint Committee on Atomic Energy was abolished and its jurisdiction was distributed among other committees with less industry-friendly membership (Temples, 1980, p. 248-250).

I collectively refer to these phenomena as "splitting the uranium triangle." This is a reference to the concept of an "iron triangle" (Adams, 1981)—an interlocking relationship between private sector interests, bureaucrats, and allied members of Congress who sit on the relevant Congressional committee. Each group provides and receives various benefits from one another, forming the basis of a mutual interest in the status quo. In the case of nuclear energy, the "uranium triangle" consisted of electric utilities, the Atomic Energy Commission (AEC), and the Joint Committee on Atomic Energy (JCAE). New civil society organizations and entrepreneurial politicians split apart the uranium triangle and forced a new paradigm in the regulation of American nuclear power plants in the 1970s.

Prior scholarship and public discourse have debated the extent to which the escalation of construction costs (Paik and Schriver, 1980; Komanoff, 1981; Cohen, 1990; Eash-Gates et al., 2020) and the dimming of the industry's fortunes generally (Quirk and Terasawa, 1981; Hultman and Koomey, 2013;

Berndt and Aldrich, 2016) can be attributed to changes in the licensing regime. I add to this debate by asking, in essence, whether increased regulatory scrutiny achieved its intended goal of improved safety. To be more precise, my research questions are as follows: (1) What variables explain the dramatic escalation in the time to license nuclear power plants in the 1970s? (2) Did the heightened public pressure and regulatory scrutiny improve the safety of nuclear power plants once in operation? Unfortunately, the data available and methods employed in the present work do not answer these questions with credible causal identification. However, they do rule out several potential sources of spurious correlation and limit the scope of possible explanations for the observed patterns in the data.

In Section 3, I present archival data quantifying various regulatory phenomena in the licensing of American nuclear power plants in the second half of the 20th century. I show that there exists an inflection point in the intensity of regulatory and political scrutiny paid to the nuclear industry, circa 1970. In Section 4, I find that state participation in the licensing process is correlated with delays, such that a one standard deviation increase in state participation is associated with a 9% longer time to receive an operating license. This relationship becomes more pronounced over time; furthermore, a tendency for more ideologically liberal states to intervene emerges in the 1970s. These findings are consistent with the existing historical literature, which now enjoy the support of fresh quantitative evidence.

In Section 5, I investigate whether regulatory scrutiny in licensing covaries with the safety of a nuclear power plant once in operation. I find that reactors which were exposed to longer review times for the issuance of an operating license exhibit lower rates of reportable safety events, a finding which is robust to a large number of controls and alternate specifications. The elasticity of this relationship is approximately -0.4; that is, a 1% increase in time spent under review for an operating licensing reduces the expected count of reportable safety events per month by 0.4%. This suggests that splitting the uranium triangle did further its intended goal of increasing the safety of American nuclear power plants.

2. Historical Context

A comprehensive narrative of the history of the regulation of nuclear power plants in the United States can be found in *A Short History of Nuclear Regulation* (Walker and Wellock, 2010). Below, I highlight phenomena and key events that illustrate the "splitting of the uranium triangle"—the dismantling of the favorable regulatory and political environment enjoyed by the nuclear industry that initially prevailed after 1954, when the Atomic Energy Act was amended to allow for private development of nuclear reactors for peaceful purposes.

While lay perception may regard the Three Mile Island accident in 1979 as the primary turning point in the fortunes of the nuclear industry, many scholars identify developments in the late 1960s and early 1970s as more important (Palfrey, 1974; Cohen, 1979; Wellock, 2012; Hultman and Koomey, 2013; Rodriguez and Weingast, 2015). For example, Green (1973, p. 512) estimates that "[b]eginning about 1968... interventions in opposition to issuance of construction permits and operating licenses became more the rule than the exception."

Prior to the emergence of nuclear power as an issue of mass controversy, opposition was essentially a localized phenomenon in response to proposals for nearby plants. Most notable among these were proposed reactors at Bodega Bay in Northern California and Ravenswood in New York City (Walker and Wellock, 2010, p. 24). New organizations and networks of activists grew out of these early experiences (Wellock, 1998).

Although the outcome desired by opponents at Bodega Bay and Ravenswood transpired—the utilities cancelled their plans after the AEC staff indicated an unfavorable outlook on licensing—these and other experiences heightened opponent's skepticism of the industry and its regulator, which they believed operated with undue secrecy and downplayed legitimate concerns for public safety. One leading anti-nuclear activist in California denounced the uranium triangle of utility, AEC, and JCAE as rule by a "small elite corps of nuclear experts"[2] and "the tyranny of scientific priesthood,"[3] espousing instead an ethic of "democratic control of technology."[4] Similar themes are present in the works of Schumacher (1973) and Lovins (1976), who advocated for "appropriate technology" and "the soft energy path," respectively. These concepts valorize consumer choice and small scale and frame nuclear power as incompatible with a democratic economy and society.

A pivotal development in the splitting of the uranium triangle was the

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[2] Wellock (1998, p. 38) (in-line quotes from original omitted)

[3] *ibid.* (p. 99) (in-line quotes from original omitted)

[4] *ibid.* (p. 117)

ruling in *Calvert Cliffs' Coordinating Committee, Inc. v. Atomic Energy Commission*, 449 F.2d 1109 (D.C. Cir. 1971). Local opponents of the Calvert Cliffs nuclear power plant in Maryland challenged the AEC's licensing procedures on the grounds that the AEC failed to adequately comply with the requirements of the recently enacted National Environmental Policy Act (NEPA). After the Appeals Court for the District of Columbia ruled against the AEC in July 1971, the Commission declined to appeal the decision further. "[R]eactor licensing came to a standstill for 18 months" while the AEC brought itself into compliance with the ruling (Bupp and Derian, 1978). In particular, the court affirmed that NEPA required the AEC to prepare its own environmental impact statement (EIS), rather than relying on reports submitted by the utility or the reviews of other federal agencies, and could not restrict its attention merely to the environmental impacts of radiologic hazards. This ruling "allow[ed] environmentalists manifold new opportunities to participate in and contest regulatory decisions" (Rodriguez and Weingast, 2015, p. 800).

While the reactors at Calvert Cliffs were ultimately granted a license to operate, the ruling corresponds closely with a change in the overall attitude of the regulator towards the industry. In August of 1971, President Nixon appointed James R. Schlesinger to the commission and designated him as chairman, replacing the outgoing Glenn T. Seaborg, who had retired after a decade of service. Whereas Seaborg was a chemist whose had worked on the Manhattan Project, Schlesinger was an economist-turned-bureaucrat, who sought to implement Nixon's agenda of environmental protection. Schlesinger and another Nixon appointee to the AEC were instrumental in the decision to not appeal the *Calvert Cliffs* decision (Walker and Wellock, 2010, pp. 45-46). In a speech before the Atomic Industrial Forum and American Nuclear Society in October of 1971, Schlesinger is quoted as saying, "You should not expect the A.E.C. to fight the industry's political, social and commercial battles. The A.E.C. exists to serve the public interest" (Lyons, 1971).

In response to public criticism from the Union of Concerned Scientists (Ford and Kendall, 1972), the AEC initiated a rulemaking in January of 1972 on the matter of emergency core cooling systems (ECCS).[5] The public hearings were held over the course of the next eighteen months and involved

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[5] The function of the ECCS is to keep the core cool in the event of an accident. It is one of several lines of defense against a meltdown.

over “20,000 pages of testimony and 30,000 pages of supporting documents” (Wellock, 2012). Participants included AEC staff, three states, several utilities, the four major reactor manufacturers, and an alliance of sixty NGOs (39 Fed. Reg. 1001). With the adoption of new criteria for the performance of ECCSs, the AEC determined that these would apply retroactively to already licensed reactors, a rare step for major new requirements (Cohen, 1979, p. 76-77).

In addition to the substantive questions regarding safety, a central theme of the hearings was “assertions by antinuclear activists that the AEC tried to cover up engineering uncertainty in its ranks by suppressing information and intimidating dissenting staff” (Wellock, 2012). The hearings attracted national attention (Lyons, 1972) and damaged the credibility of the AEC (Joppke, 1993, p. 30; Walker and Wellock, 2010, p. 37), contributing to Congress’s decision to abolish the AEC and vest its regulatory responsibilities in a new agency, the NRC, which began operation in 1975.

The splitting of the uranium triangle was completed with the abolition of the JCAE in 1977. “This development was actually the culmination of a series of legislative defeats for the JCAE on specific issues...” and was facilitated by the defeat or retirement of several long-time JCAE members in the 1976 Congressional elections (Temples, 1980, pp. 249-250). Its jurisdiction was reallocated to other committees with less industry-friendly membership.

Among the remaining events and phenomena of interest to the present work, there is, of course, the accident at Three Mile Island on March 28th, 1979.[6] The immediate impact of the event on licensing was a “licensing pause,” as staff resources were temporarily redirected toward responding to the emergency, understand its causes, and reviewing existing regulations for possible revisions. The licensing pause lasted until February 1980 (Walker and Wellock, 2010, p. 59).

By the 1980s, the nuclear industry was widely considered to be “in decline.” No new NPPs were proposed for construction; many reactors under construction were abandoned due to high real interest rates, lower demand forecasts, and construction costs far in excess of budgeted amounts. The only licensing activity to speak of was the issuance of operating licenses for reactors still under construction. Joppke (1992) summarizes the major

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[6] Should the reader desire an introduction to the technical details of the event explained for a lay audience, I suggest pp. 53-58 in Walker and Wellock (2010).

developments of this period. While activist attention on civilian nuclear reactors faded and was redirected toward the Reagan administration's nuclear weapons build-up, state governments kept up the fight against nuclear power on three issues: nuclear waste policy, utility rate regulation, and a refusal to cooperate on emergency planning as a tactic to stymie the issuance of operating licenses.

2.1. Prior Literature: Causes and Consequences

In comparative study of Japan and the United States, Cohen, McCubbins and Rosenbluth (1995) argue that a multiplicity of veto points in the constitutional design of the United States enabled vigorous political contestation of nuclear policy, including at the state and local level.

I refer the reader to Temples (1980) for an authoritative and near-contemporaneous account of how "[l]itigation, research, and lobbying by [anti-nuclear] individuals and groups helped focus greater public, media, and Congressional attention" on the environmental impacts and safety risks of nuclear power in the United States. Rodriguez and Weingast (2015) argue that the political branches of the federal government (i.e. Congress and the President) played important roles in transforming administrative law to be more accommodating to the demands and interests of activists through legislation and executive orders, which they illustrate with the case of nuclear power. Joppke (1993, p. 55) presents the view that these two developments were mutually reinforcing: "[t]his shift means that public-interest lobbies have found access to a policy arena, while friendly legislators seek to further their popularity by representing the widely dispersed beneficiaries of proposed regulation—at the cost of producers."

Fremeth, Holburn and Piazza (2021) find that antinuclear protests which occurring near proposed or operating nuclear power plants were associated with their utility owners subsequently receiving lower regulated rates of return by the decisions of state public utility commissions.

The present work is a spiritual successor of Cohen (1979). She coded the content of objections lodged by intervenors in public hearings for construction permits, determined the resolution of those objections, and estimated their impact on the duration of the licensing process. Cohen found that substantive objections (as contrasted with process objections) were rejected or set aside in 89 out of 103 instances. Only four instances were classified as "major" objections which were granted by the hearing officers to have merit. Success was somewhat more common when the objection was process-related, with only 21 out of 40 being rejected or set aside. These summary statistics are consistent with the view espoused by anti-nuclear activist and lawyer Terry Lodge of Toledo, Ohio: "[nuclear power] collapsed under its own weight... We were gnats flying around the giant's head. Whether we got slapped didn't matter because the giant was going to do whatever the giant was going to do." (Wellock, 1998, p. 3)

However, in Cohen's analysis of CP licensing times, certain types of objections were substantially associated with delayed issuance of the permit. As with the methods of the present work, the regression in Table V of Cohen (1979) employs year fixed effects, which isolates the cross-sectional variation. In other words, the comparison is among reactor licensing cases in the same year but varying types of intervenor objections (if any), which eliminates the possibility that the results are simply an artefact of spurious time trends.

Hearings in which objections were raised concerning compliance with NEPA and the EIS took 6.4 months longer on average (std. error: 3.4 months). When objections were raised regarding the safety of the plant in preventing or containing accidents, an additional 11.2 months (std. error: 3.5 months). For a catch-all category of objections related to quality assurance, evacuation plans, and plant security, the expected delay was 7.1 months (std. error: 2.9). Other types of objections—specifically those related to procedure, substantive questions of environmental protection, and radiologic hazards from routine operation—had statistically null effects on the time to receive a license. Cohen (p. 68) summarizes her conclusions as follows:

> *Delays in licensing are found to be mainly due to consideration by the NRC staff of important substantive issues. Moreover, the issues concern safety and environmental standards, rather than any particular plant design. Furthermore, delay does not result from public participants simply manipulating the process so as to hold up licensing, e.g., with procedural maneuvers or legalistic strategies. Such attempts are by and large unsuccessful. The study of licensing cases suggests that licensing delays are due primarily to NRC uncertainties about reactor safety. Consequently, recent proposals to streamline licensing may be considered a threat to safety.*

However, at the time of writing of Cohen (1979), little if any empirical data was available to test whether licensing delays actually contributed to improved reactor safety. I explore this question in Section 5.

3. Archival Evidence for the Regulatory Revolution

In this section, I present observational data to support the claim that the quantity and complexity of regulatory requirements faced by the nuclear industry in the United States increased over time, with an approximate inflection point of 1970. A complete description of the sources, collection, cleaning, and transformation of the data can be found in Appendix B. Below, I describe the variables at a high level and present the data graphically.

3.1. The Licensing Hold-Up

In Figure 1, I plot the licensing review time for each CP—the duration in months from docketing of the application to issued of the permit by AEC / NRC—against the date docketed. I color code each observation according to whether (1) the CP was issued prior to the *Calvert Cliffs* decision, (2) the application was docketed prior but the CP was issued after the decision, or (3) the application was docketed after the decision. The mean review time for each of these groups was (1) 14 months, (2) 40 months, and (3) 33 months, respectively.

The graph is consistent with claims that the *Calvert Cliffs* decision contributed to a hold-up in the licensing of reactors as a result of the new, unanticipated requirement for the AEC to prepare environmental impact statements. The modestly shorter lead time for reactors whose applications were docketed after the decision may be explained by the conjecture that anticipation of the requirements enabled more timely completion of the review. This graphical presentation of the data matches the regression results of in Table V of (Cohen, 1979), who finds that CP applications docketed in 1970 and 1971 experienced the longest review times.

However, there are clear pre-trends in the late 1960s among reactors which ultimately received their construction permit prior to the *Calvert Cliffs* decision, so it is not credible to attribute all patterns in Figure 1 to the effect of the court's ruling.

In Figure 2, I plot an equivalent graph for the time required to review an application for an OL. Being under review during the *Calvert Cliffs* decision is related to having a longer review time (mean: 46 months) compared to reactors which received their OL prior to the decision (mean: 21 months).

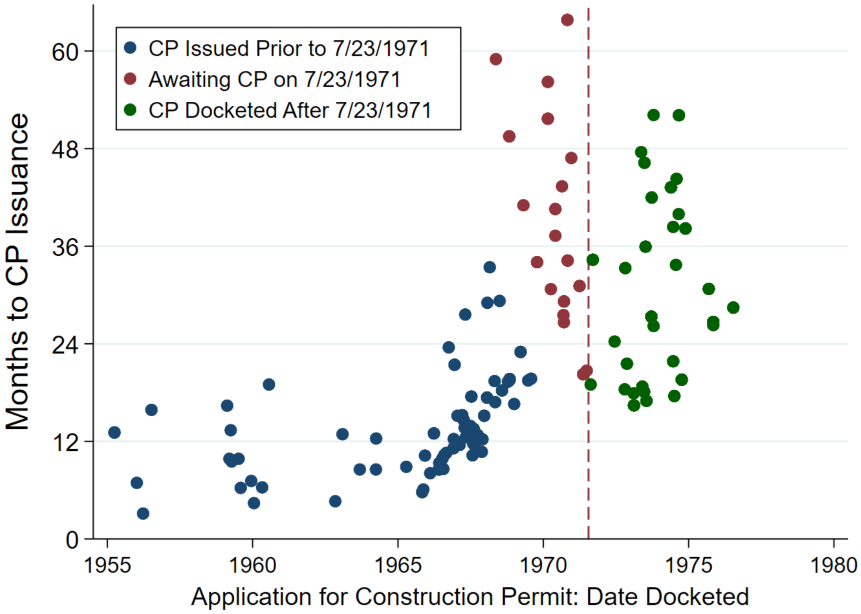


Figure 1: Trends in Construction Permitting of U.S. NPPs

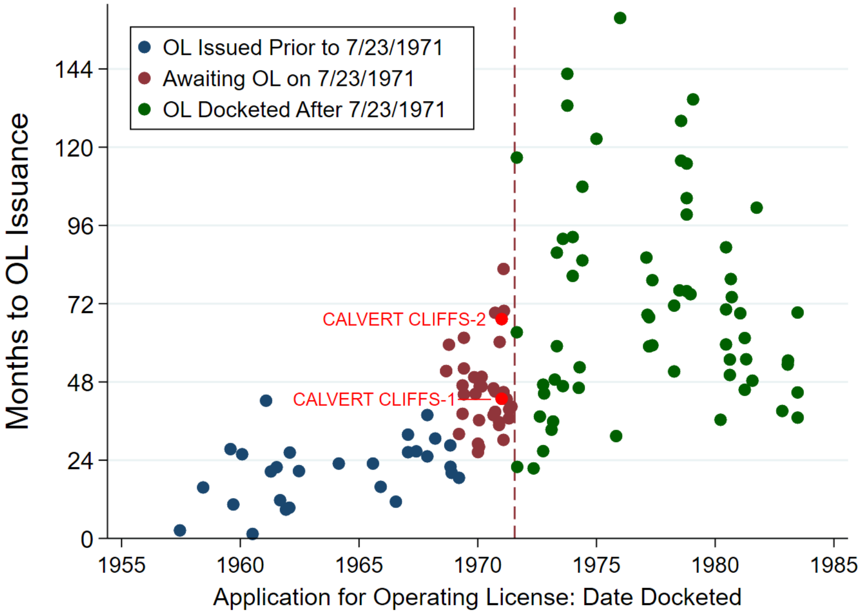


Figure 2: Trends in Operational Licensing of U.S. NPPs

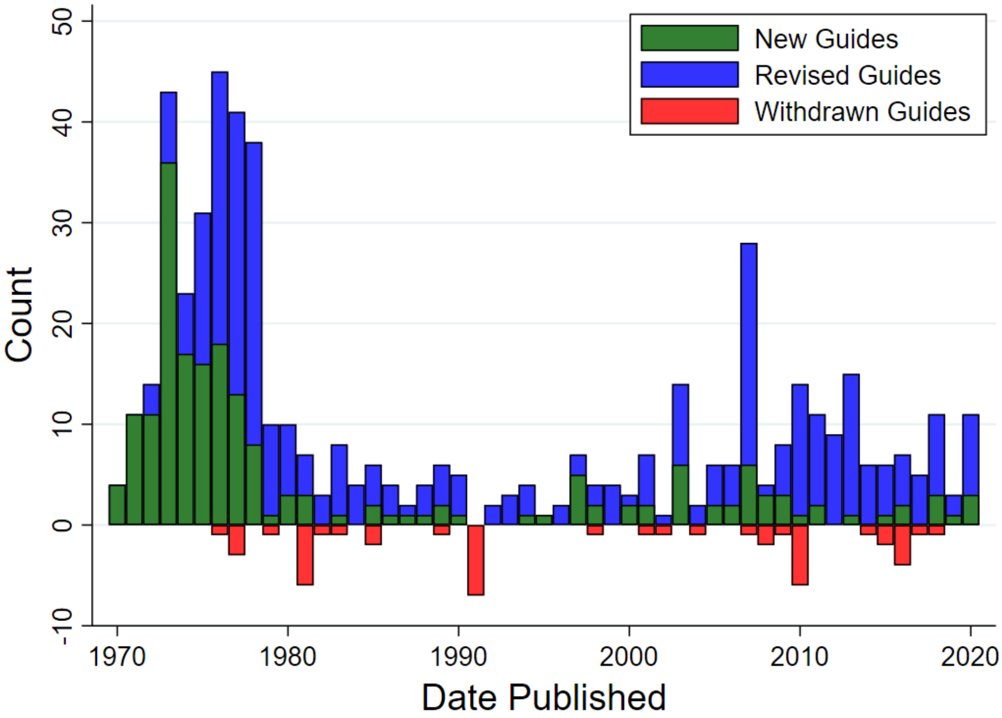


Figure 3: Publication of Regulatory Guides Relating to the Design or Construction of Nuclear Power Plants by Year

On the graph I indicate in bright red the observations correspond to Calvert Cliffs Units 1 & 2, the eponymous reactors at the center of the court case, for the interest of the reader. These two reactors were awaiting issuance of their operating licenses at the time the legal challenge was brought.

Unlike with construction permits, licensing review of operating licenses continued to stretch out further in the 1970s, with the trend finally abating and reversing in the 1980s. This suggests that temporary disruption from new EIS paperwork is not sufficient to explain the trend.

3.2. Turbulent Regulatory Guidance

In Figure 3, I plot the count of newly issued, revised, and withdrawn regulatory guides relating to the design or construction of nuclear power plants by year of publication. Regulatory guides are (were) documents prepared by the NRC (AEC) staff. The first regulatory guides were introduced in

November of 1970 in order to help applicants better navigate the increasing thicket of regulations and required documentation. Regulatory guides are not themselves binding regulations; rather, they are interpretations of the regulations and recommendations from the staff to expedite the process and increase the chances of a favorable review.

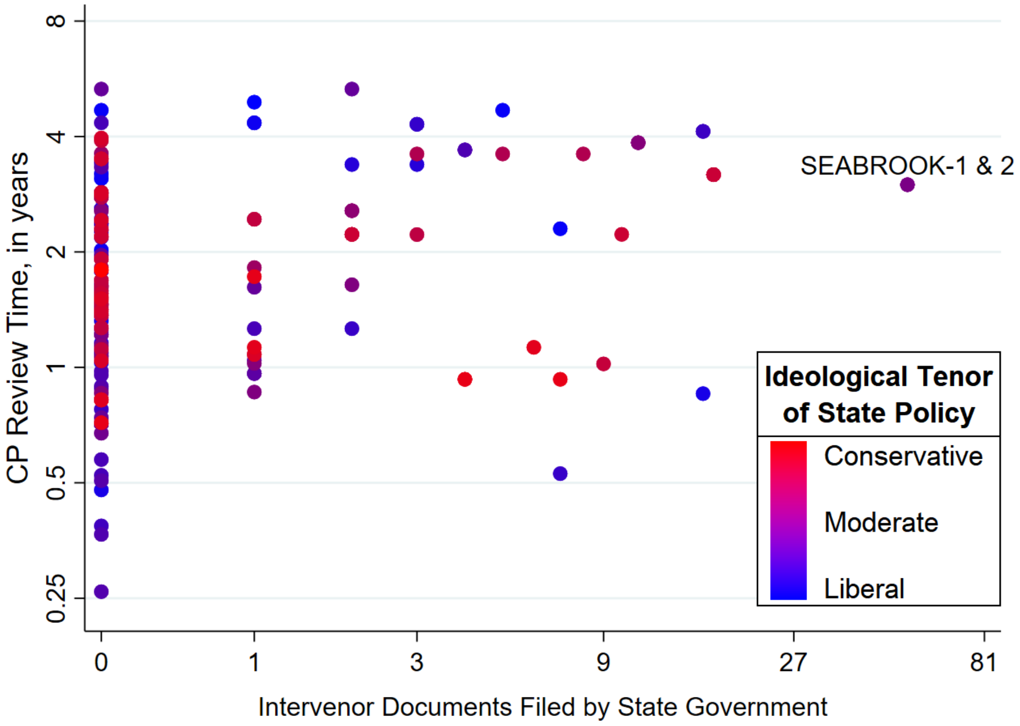
In Appendix B.1, I document the data sources and cleaning procedures, particularly the exclusion of regulatory guides that do not relate to nuclear power plants and those of a purely clerical nature. I also elaborate the challenges involved in obtaining equivalent data for revisions to the relevant sections of the Code of Federal Regulations, an effort which is beyond the scope of the present work.

A primary disadvantage of regulatory guides is that they do not provide a basis for comparing the years prior to 1970 with those after 1970. On the other hand, the decision to introduce supplementary documents to "assist" utilities in complying with the regulations is qualitatively indicative of a change in the quantity and complexity of the regulatory requirements. Another difficulty in the interpretation of the data is that many of the "new" regulatory guides in the early 1970s may represent guidance for long-established regulations, so the large number of new guides may exaggerate the true degree of regulatory turbulence in the 1970s. Further research would be needed to discriminate between regulatory guides corresponding to new rather than existing requirements. With these disclaimers in mind, I will comment on the patterns apparent in the data.

The 1970s were a decade of tremendous regulatory turbulence for the nuclear industry when contrasted with any decade that followed. The AEC and NRC staff issued new guides at a blistering pace in the early 1970s, reaching a maximum of 36 (3 per month) in 1973. The first revisions to the guides were made in 1972 and they reached a maximum of 30 in 1978. The publication of new and revised regulatory guides for design and construction began to slow down in 1979, perhaps on account of the lack of new reactors submitted for licensing or perhaps because the staff's time and attention was diverted by the Three Mile Island (TMI) accident.

From 1979 to the early 2000s, the pace of regulatory guide issuance remained comparatively low and steady. Revisions to the guides picked up again during the anticipated "nuclear renaissance." While actual construction of new nuclear power plants has not met expectations, the level of regulatory activity reflects the much larger universe of applications for design certification and permits to construct and operate new reactors.

Figure 4: State Participation in CP Proceedings



A substantial number of guides were withdrawn in 1981, 1991, and 2010. "Regulatory guides may be withdrawn when they are superseded by the Commission's regulations, when equivalent recommendations have been incorporated in applicable approved codes and standards, or when changes in methods and techniques or in the need for specific guidance have made them obsolete" (56 Fed. Reg. 30777). Overall, there is no particular pattern to withdrawals. My qualitative impression from statements made at announcing withdrawals of regulatory guides is that the NRC staff periodically review the existing regulatory guides without any particular impetus, to revise or withdraw them as appropriate.

3.3. State Intervention in Licensing

Figure 4 is dense with information, so I will explain each element one at a time. Each observation represents the proceedings for the review and granting of the construction permit of one reactor. If a reactor does not complete the licensing process, then it is not represented in the figure.[7] The observations are color-coded to indicate the ideological tenor of policy in the state where the reactor is located, as of the year the application for the CP was docketed. The source of the data for this variable is provided in Appendix C.

The Y-axis measures the length of time from the docketing of the application for an CP to the issuance of the GP. This variable has been transformed with the natural logarithm; the tick marks on the Y-axis are evenly spaced by powers of 2 for ease of interpretation. The X-axis measures the count of documents docketed in the proceeding, prior to the granting of a CP, whose author was affiliated with the government of the state where the reactor is located. This variable has been transformed by the inverse hyperbolic sine function, which is approximately logarithmic, except that $sinh^{-1}(0) = 0$. The X-axis is scaled by powers of 3, for consistency with Figure 5.

Overall, the picture provided by Figure 4 is not indicative of any particular relationship in the data. The only noteworthy observations in terms of substantial state participation are the reactors at Seabrook, in New Hampshire.

Figure 5 is equivalent to Figure 4 except that it displays data for state participation in the proceedings for operating licenses. Figure 5 exhibits an unmistakable positive correlation between the number of documents filed and the time involved in the issuance of an operating license. Here, the quasi-logarithmic scaling of the X-axis is especially necessary to accommodate four outliers, which are labeled on the graph: Shoreham, Seabrook Unit 1,[8] and Diablo Canyon Units 1 & 2.

Two noteworthy outliers in the Y-dimension are Watts Bar 1 & 2. The long time required for them to received their operating licenses reflects the fact construction was suspended after their applications for OLs had been docketed. Given how few documents by the State of Tennessee show up in the NRC dockets for these reactors, it seems unlikely that state opposition was a meaningful factor explaining the extraordinary delays.

When comparing Figures 4 and 5, the overall level of state engagement with CP proceedings is much lower than with OL proceedings. The mean

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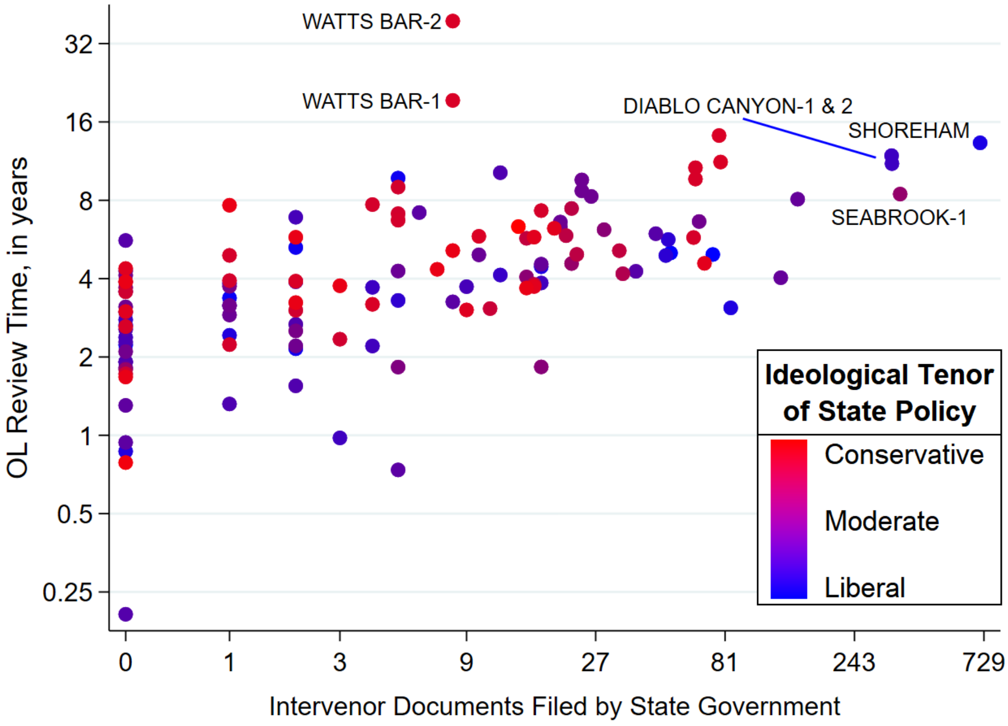
[7] In very case, non-completion reflects withdrawal of the application by the utility. There are no rejected licenses.

[8] Construction of Seabrook Unit 2 was abandoned for economic reasons. Thus, it never received an OL and cannot be displayed on this graph.

Figure 5: State Participation in OL Proceedings



number of documents in the 173 CP proceedings that reached a conclusion[9] is 2.2, with zero documents in 68% of cases. For the 127 OL proceedings which reached a conclusion, the mean is 28.3, with zero documents in only 24% of cases.

I also collected equivalent data on county government participation in licensing. The graphs corresponding to county intervention are not presented as zero documents by county-affiliated authors were found in 95% of CP proceedings and 78% of OL proceedings. The only reactor with noteworthy levels of county participation is the Shoreham reactor on Long Island, which was bitterly contested by Suffolk County (alongside the State of New York) during the OL proceedings on the grounds that Long Island could not feasibly be evacuated in the event of an emergency.

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[9] As opposed to terminating due to withdrawal by the utility.

3.4. Amendments to Safety Analysis Reports

One of the key documents required for a construction permit is the Preliminary Safety Analysis Report (PSAR). The PSAR is “preliminary” insofar as the design of the plant need not be finalized prior to the issuance of the CP. Instead, the Final Safety Analysis Report (FSAR) is required with the application for an operating license, which is then reviewed while the plant finishes construction. The industry’s predilection for starting construction on plants with incomplete designs has been widely criticized as a source of mishaps, delay, and cost overrun (Koomey and Hultman, 2007; Gogan et al., 2018).

The safety analysis reports describe the design of the facility, lay out a plan for quality assurance in material and equipment, propose operating limits, and analyze the safety of the facility. The primary audience for these reports were the AEC/NRC staff, who review them for completeness and substantive compliance with safety regulations. Inadequately detailed safety analysis reports were a sufficiently routine problem that it stimulated the development of several of the earliest regulatory guides.

When safety analysis reports are either incomplete or do not assure adequate safety in the opinion of the staff, the staff will inform the applicant and request amendments. This can entail substantive changes to the design of the plant. To a certain extent, the applicant has the option of ignoring the request and hoping that an unfavorable review by the staff does not jeopardize issuance of the license by vote of the Commission, but in practice, applicants routinely comply with staff requests for amendments. Amendments can also occur if the design of the plant changes for reasons external to the regulatory review process.

In Figures 6 and 7, I plot the number of amendments to the PSAR and FSAR for each reactor against the date the applications for CP and OL were docketed. I label noteworthy outliers for the interest of the reader. For PSARs, there is no discernible trend. For FSARs, there is a clear upward trend in the number of amendments starting from the late 1960s.

In the case of FSARs, I also label three groups of reactors which are not outliers but are of interest on account of their standardized designs and comparatively lower number of FSAR amendments for their era. These are

Figure 6: Amendments to Preliminary Safety Analysis Reports in CP Licensing Cases

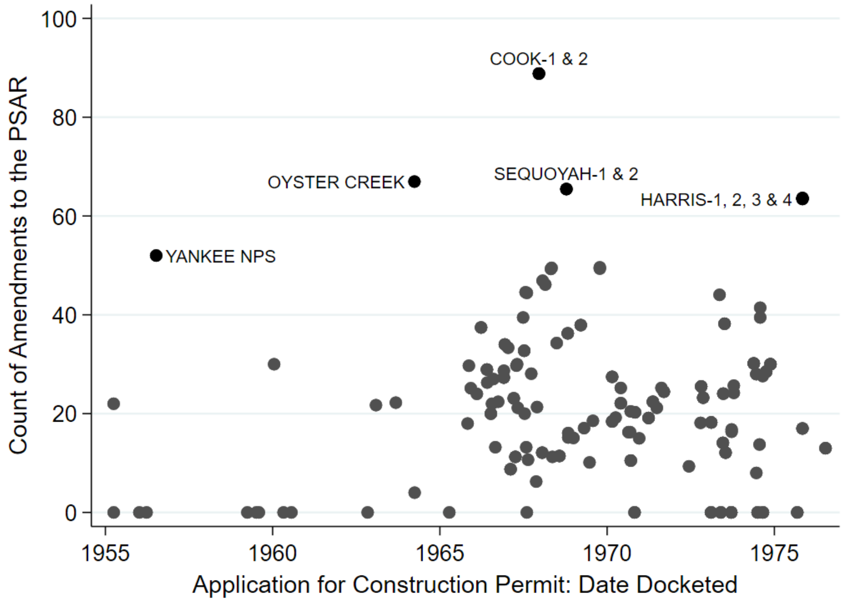
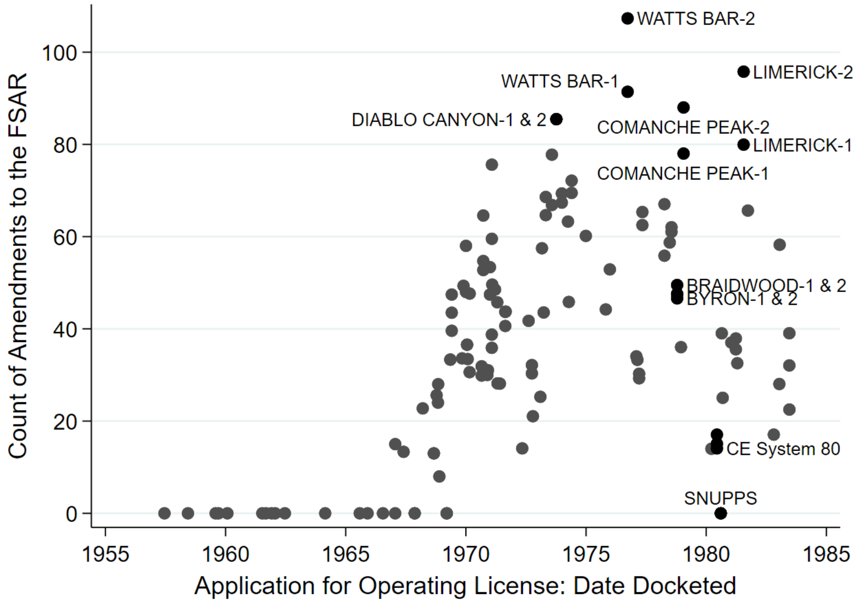


Figure 7: Amendments to Final Safety Analysis Reports in OL Licensing Cases



the SNUPPS[10] plants (Callway and Wolf Creek),[11] the System 80 reactors by Combustion Engineering (of which only three were ultimately completed, Palo Verde Units 1-3), and the Braidwood and Byron reactors (which were ordered as four identical reactors, two at each site). The relatively fewer FSAR amendments for these reactors is mildly supportive of the idea that standardization of design streamlined the licensing process, but the sample size is too small to draw any firm conclusions.

4. Covariates of the Licensing Hold-Up

In this section, I investigate the covariates of the licensing hold-up, i.e. the increasing lead times required to secure a CP and OL as exhibited in Figures 1 and 2. I say "covariates" and not "causes" because causal identification is not achieved with the present methods.

4.1. Model Specification

I consider three distinct dependent variables: (1) the time to review a CP (from docketing to issuance), (2) the time to review an OL (frock docketing to issuance), and (3) total lead time (from docketing of the application for the CP to the commencement of commercial operation). The empirical distributions of all dependents variables have long right-tails, so I apply a log-transformation. A symmetric distribution of errors implied by a linear model is unrealistic in view of the data-generating process. In both NPP construction and licensing, there are several interdependent steps. A random shock that delays one step will have knock-on effects for the entire project timeline; a random shock that results in early completion of one step will not necessarily enable faster completion if the duration of a parallel step prevents proceeding to a later step (Stewart et al., 2022).

In each regression, I include fixed effects by the year in which "the clock starts ticking" for the measurement of the dependent variable. This ensures that reactors are compared strictly cross-sectionally, thereby removing any possible spurious association that might arise from common time trends. Of course, longitudinal differences in the independent variables are almost surely causally related to the licensing hold-up observed in Figures 1 and 2 but

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[10] An acronym for "Standardized Nuclear Unit Power Plant System"

[11] These reactors had their applications docketed on the same date, so they appear as a single observation on the graph.

the present methods cannot distinguish such effects from other time-related trends.

Among the independent variables, I include state and county intervenor activity. These variables are computed slightly differently depending on the dependent variable. For CP review time, I count all documents authored by the government in the docket of reactor i prior to CP issuance for reactor i are counted. For OL review time, I count all documents after CP issuance but prior to OL issuance for reactor i are counted. For total lead time, I count all documents prior to OL issuance; I exclude documents after OL issuance and prior to commercial operation on the grounds that, once the OL is issued, the intervenor cannot halt or delay operation through participation in the licensing process. All counts of documents are transformed using the inverse hyerpoblic sine function, for the reasons discussed in Section 3.3.

The next set of independent variables of interest are the counts of amendments to the PSAR and FSAR. The count of PSAR amendments is excluded for the regression of OL review time, as the PSAR only pertains to construction permitting. Likewise, the count of FSAR amendments is excluded from the regression of CP review time.

Because regulatory guides vary longitudinally but not cross-sectionally, they are not included as an independent variables in any regressions. The partial association between an outcome and a time series cannot be estimated in the presence of time fixed effects.

The remaining variables are primarily included as controls. These are nameplate electric capacity, a dummy variable for investor-ownership, months of construction suspension, and a control for measurement error relating to multi-unit construction, which is described in detail in Appendix A. Nameplate electric capacity and months of construction suspension enter into the right-hand side of the equation linearly because experience from Benson (2022) indicates that a log-linear functional form has the best fit to the data for these variables as predictors of construction duration.

4.2. Results

Table 1 displays the regression results for the models described in Section 4.1. I find that state participation in the licensing process is positively associated with the time required to received a license and begin commercial operation. A one standard deviation increase in documents docketed by the state is associated with the licensing review time and total lead time taking around 9% to 10% longer. Conversely, county participation has no

Dependent Variable: $ln(Date_1 - Date_0)$

	(1)	(2)	(3)
$\mathbf{Date_1}$	CP Issued	OL Issued	Comm. Op.
$\mathbf{Date_0}$	CP Docketed	OL Docketed	CP Docketed
State Intervenor Activity	**9.8%**	**9.3%**	**9.5%**
one S.D. of $sinh^{-1}(\sum Docs_{it})$	(3.20)	(1.93)	(2.41)
County Intervenor Activity	**1.9%**	**4.8%**	**4.1%**
one S.D. of $sinh^{-1}(\sum Docs_{it})$	(0.54)	(1.70)	(1.89)
Amendments to PSAR	**3.5%**		**-1.0%**
one S.D. of count of $Amends_i$	(0.97)		(-0.48)
Amendments to FSAR		**28.8%**	**15.1%**
one S.D. of count of $Amends_i$		(4.46)	(3.50)
Nameplate Electric Capacity	**-0.2%**	**7.3%**	**3.7%**
100 MWe (original net rating)	(-0.09)	(3.13)	(1.54)
Investor-Owned Utility	**6.7%**	**-12.8%**	**-9.8%**
$IOU_i = 1$ *if investor-owned*	(0.76)	(-1.44)	(-1.68)
Construction Suspension		**0.3%**	**0.3%**
duration in months		(4.09)	(7.41)
Multi-Unit Construction			**8.2%**
M_i (see Appendix A.1)			(2.57)
Fixed Effects by Year of ...	$Date_0$	$Date_0$	$Date_0$
Within R^2	.131	.386	.489
Observations	169	122	126

Transformed marginal effects on $date_1 - date_0$ in **bold.** (t-statistics in parentheses.)

Table 1: Cross-Sectional Covariates of Lead Time in American NPP Licensing and Construction

Dependent Variable: $ln(Date_1 - Date_0)$

	(2)	(2a)	(2b)	(2c)
State Intervenor Activity	**9.3%**	**11.0%**	**14.8%**	**30.8%**
one S.D. of $sinh^{-1}(\sum Docs_{it})$	(1.93)	(2.40)	(3.17)	(2.74)
Amendments to FSAR	**28.8%**	**27.7%**	**26.4%**	**16.2%**
one S.D. of count of $Amends_i$	(4.46)	(4.35)	(3.66)	(1.61)
OL Docketed In or After	1957	1965	1970	1975
Observations	122	115	92	43

Transformed marginal effects in **bold.** (t-statistics in parentheses.)

Table 2: Reestimating Model (2) of Table 1 with Sample Restrictions—Marginal Effect of Covariates of Interest on Time to OL Issuance

statistically significant association; the estimated magnitude of the effect of county participation is less than half the size of the effect estimated for state participation.

Amendments to the FSAR strongly predict delays in the issuance of an operating license, but amendments to the PSAR seem to have negligible effects on the time to issue a construction permit. The effect of FSAR amendments carries over in delaying commercial operation as well, although not as strongly, which follows from the fact that amendments to the FSAR occur relatively late in the overall lead time.

In Table 2, I evaluate the robustness of the findings regarding state intervenor activity and amendments to the FSAR. I rerun the regression in Model (2)[12] with increasing sample restriction by date to evaluate the sensitivity of the results to differential levels of document survival from different years. We would expect attenuation bias and imprecise estimates when including observations from earlier eras, as the rate of document survival in the NRC's library should be lower for older documents. This hypothesis can be clearly rejected when considering the effect of amendments to the FSAR, as the effect size is strongest and most precisely estimated when using the full sample.

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[12] I include the same variables in all cases but only display the coefficients of interest in Table 2.

I do find that the effect size grows for state intervenor activity as the sample is narrowed to exclude older reactors. This pattern is consistent with the hypothesis regarding document survival, but it also may reflect a heterogeneous treatment effect[13] over time. The especially large coefficient for reactors whose application for an OL was docketed in or after 1975 is consistent with the argument of Joppke (1992), namely that "federal frag-

Dependent Variable: *one S.D. of* $sinh^{-1}(\sum Docs_{it})$

		Proceeding	CP	OL
Treatment	×	*Calvert Cliffs* ruling	(1)	(2)
one S.D. increase in **Policy Liberalism** *of state law as of* $Date_0$		License Issued Prior to 7/23/1971	**-0.13**	**-0.25**
			(-0.73)	(-0.46)
		License Under Review on 7/23/1971	**0.33**	**0.08**
			(1.97)	(0.25)
		Application Docketed after 7/23/1971	**-0.11**	**0.85**
			(-0.49)	(3.20)
		Observations	171	127
			(3)	(4)
one S.D. increase in **Voter Liberalism** *of the state electorate as of* $Date_0$		License Issued Prior to 7/23/1971	**-0.07**	**0.08**
			(-0.58)	(0.21)
		License Under Review on 7/23/1971	**0.27**	**-0.01**
			(1.72)	(-0.02)
		Application Docketed after 7/23/1971	**-0.05**	**0.72**
			(-0.36)	(2.77)
		Observations	163	125
Fixed Effects by Year of...			CP Docketed	OL Docketed

Standardized marginal effects in **bold.** (t-statistics in parentheses.)

Table 3: Cross-Sectional Relationship between State Politics and Intervenor Activity by State Government in AEC/NRC Licensing Cases

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[13] I say "treatment effect" to refer to the underlying causal mechanism which I theorize drives the observed partial association. The use of "treatment effect" should not be constructed to claim causal identification with the present methods.

mentation of authority became... the central barrier to the economic and political recovery of American nuclear power... in the 1980s" (p. 711).

In light of this finding and considering the historical timing of when nuclear power became a salient political issue, I perform an auxiliary analysis to examine when and how state-level politics correspond with state intervention. In Table 3, I present estimates of the association between a state's ideological lean with the level of that state's participation in the licensing of reactor in its jurisdiction. All variables have been standardized for ease of interpretation. All models include fixed effects by the year the proceeding began, to isolate the cross-sectional variation.

There are four models, two for the CP review and two for the OL review. The political environment of the state is measured with two distinct variables, namely the ideology of state policy and the ideology of the state's voters (see Appendix C for sources and definitions), for robustness. The political variables are interacted with indicator variables based on the timing of the licensing relative to the *Calvert cliffs* decision. I do not purport to attribute differences in the coefficients to the *Calvert cliffs* decision alone. Rather, the decision is a representative inflection point in the national debate over nuclear power. I am testing for the hypotheses that (1) state intervenor activity is ideologically motivated, and (2) that such an ideological motivation may have strengthened over time.

The results are presented in in Table 3. Most coefficients are statistically indistinguishable from a null effect. There are one and a half exceptions. In construction permitting, the liberalism of a state's politics is weakly associated with increased intervenor activity specifically in cases that were under review at the time of the *Calvert Cliffs* decision, but not at other times. The effect is similarly modest in magnitude for both measures of liberalism and of marginal to weak statistical significance. It seems plausible that more liberal states were activated by the environmental issues raised by the *Calvert Cliffs* decision, but if so, I would expect the relationship to hold in the post-*Calvert Cliffs* era. Therefore, I do not attribute much credibility to this marginally significant finding.

In the post-*Calvert Cliffs* era, the liberalism of a state's politics is a very strong predictor of its level of participation in the OL proceedings of reactors in its jurisdiction. This effect is strongly statistically significant and fairly large in magnitude. Averaging the two coefficients in Model (2) and Model (4) together, the interpretation is as follows: a one standard deviation increase in liberalism is associated with a 0.79 standard deviation increase in the number of documents the state files when intervening in the operational licensing of a reactor. That this relationship does not seem to exist prior to the *Calvert Cliffs* decision may be explained by the relatively low salience of nuclear power as a political issue prior to the 1970s.

I posit that these findings are consistent with the following interpretation: ideological liberals soured on nuclear power in the 1970s, so liberal state governments become more involved in reactor licensing in the 1970s (as well as the 1980s for those reactors which took that long to finish construction and licensed). State involvement became more oppositional in character, generating longer delays in licensing. However, as I have not analyzed the substantive content of intevenor documents, the claim that state involvement in licensing was more oppositional in character has not been quantitatively tested here. I rely on the prior qualitative work of Surrey and Huggett (1976), Joppke (1992), Wellock (1998) to justify that particular claim.

5. Operational Safety

To measure operational safety, I construct a monthly panel of the count of Licensee Event Reports (LERs) submitted to the NRC for each operating reactor. These reports are required by NRC regulations and document adverse events relevant to the safety of the plant. Examples of reportable events include plant operation in violation of technical specifications, the discovery of degraded conditions affecting safety systems, unplanned reactor trips and scrams, the failure of safety systems to operate as intended, and radioactive releases beyond regulated limits.

At the inception of the LER program, the conditions which triggered the filing of an LER were specified by the operating license of each reactor. Starting on January 1st, 1984, new NRC regulations entered into effect which established standard and universal reporting requirements, superseding any former license-specific requirements. Therefore, the analysis which follows restricts the sample to the years 1984 to 2020, inclusive. Further details—including documentation of the data collection process—are available in Appendix B.3.

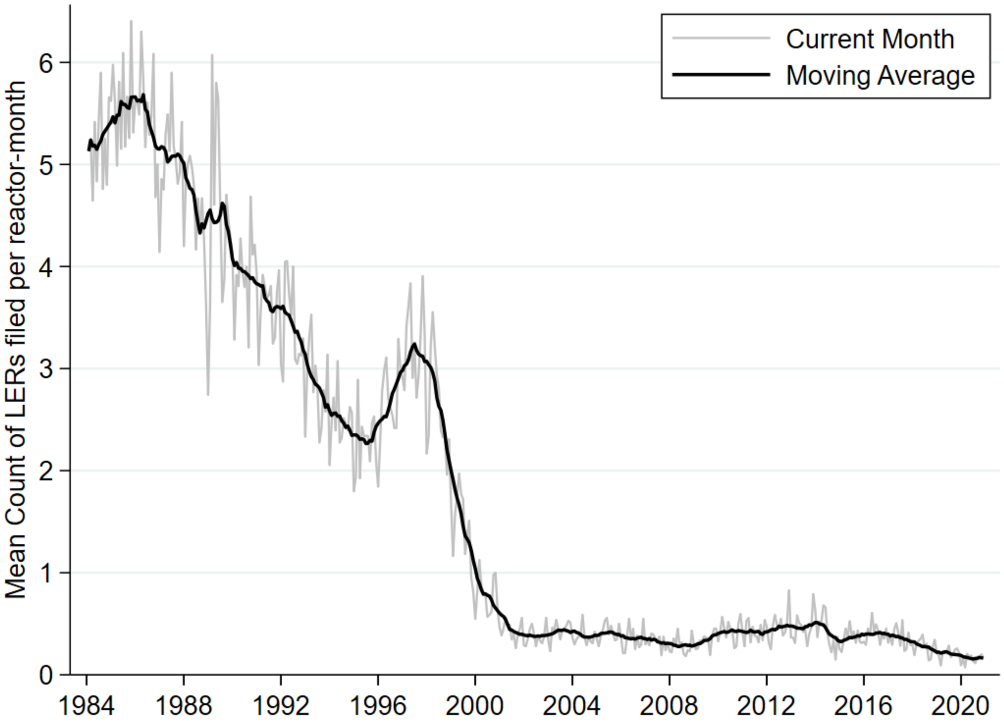

Figure 8: Average Rate of LER filing per Reactor

5.1. Trends in Licensee Event Reports

Figure 8 plots the time trend in the average number of LERs filed per month for operational[14] reactors. In the mid-1980s, the typical reactor averaged about five reports per month. The years 1986 to 1995 exhibit a relatively steady trend of improvement in safety, followed by a modest rise in the late ‘90s and a precipitous drop around the turn of the millennium. Since 2001, the rate of issuance has plateaued, averaging around one LER every three months.

Under casual inspection, the sharp decline in LERs roughly coincides with the NRC's transition to a digitized document library on November 1st,

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[14] By "operational," I exclude reactors still under construction or commissioning and those reactors which have retired. Reactors under long-term but temporary shut-down, such as those at Browns Ferry, are not excluded for lack of complete data identifying all such periods of extended non-operation.

1999. This raises questions about data quality attributable to differences in document survival before and after this date. My subjective impression based on having gathered the data is that the complete universe of bibliographic records for Licensee Event Reports is indeed available from the NRC's online library, certainly from 1984 onward. In any case, a reduction in LERs is inconsistent with the most plausible hypothesis regarding any differences in document survival: older, pre-digital documents should be expected to survive at *lower* rates than more recent, digitized documents.

In Appendix B.3, I present a survey of all revisions to 10 CFR 50.73—the relevant section of the Code of Federal Regulations—since its introduction. I find that the only substantive change is an extensive set revisions with an effective date of January 23rd, 2001.[15]. This change in the regulations governing the criteria for LERs occurs after the sharp declines of the late 1990s, and therefore cannot explain it.

Per the findings of Davis and Wolfram (2012), dramatic improvements in the reliability of American nuclear power plants were underway at this time, which is consistent with the apparent trend in LERs. In unreported regressions, I find a statistically significant but substantively small relationship between the unplanned capability loss factor (UCL) (see Appendix A and the count of LERs filed. Ultimately, industry-wide longitudinal trends in the operational safety of American nuclear power plants are not central to the analysis. For this reason, I introduce year fixed effects, absorbing common variation in the time dimension.

However, the entry of newer reactors (which one might expect are safer) and the exit of early-vintage reactors (which one might expect are less safe) changes the composition of the population over time. There remains the possibility that the characteristics of older reactor (e.g. less regulatory burden) would be spuriously correlated with LER filings simply because older reactors were less likely to be operating in the 21st century, when the industry had achieved very low rates of LER filings, whether due to learning by plant operators or revisions in regulatory requirements.

To isolate the extent of within-reactor, over time changes in the rate of LER issuance, I regress the count of LERs in a given month on fixed effects by reactor (indexed by i), year (indexed by y), and calendar month (indexed

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[15] 65 FR 63787

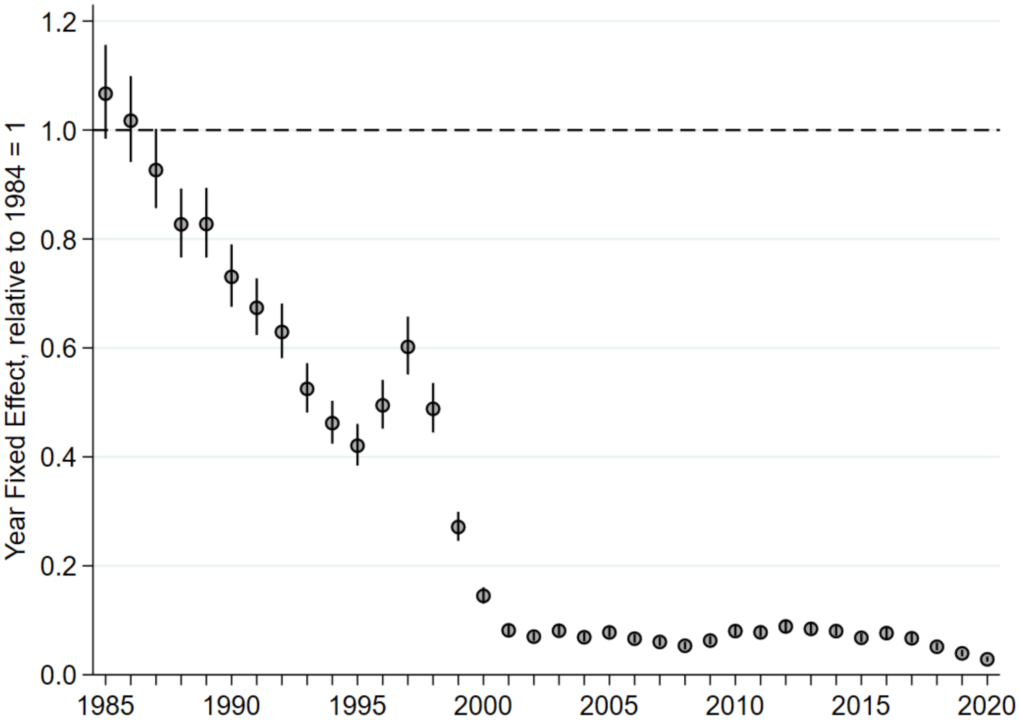

Figure 9: Year Fixed Effects Estimated by Eq. 1, de-transformed (e^{β_t})

by m):

$$ln(E\big[LER_{it}\big]) = \alpha_i + \beta_y + \gamma_m \tag{1}$$

The outcome is count data; hence, I estimate the model by Poisson regression, which does not include an error term. The time index t on LER_{it} refers to the month and year of observation. The right side of the equation separates the calendar month from the year to allow the model to capture the seasonality in the electricity sector—nuclear power plants typically schedule their refueling and maintenance outages in the fall or spring. I hypothesize that this seasonality will be reflected in the rate of LER issuance.

Figure 9 displays the estimated year fixed effects, after reversing the log-transformation. 1984 was chosen as the omitted category, so the resulting values can be interpreted relative to a baseline of $exp(\beta_{1984}) = e^0 = 1$. Figure 9 strongly indicates that the same reactors have seen large reductions in their own rate of LER issuance over time. The typical reactor filed 97.2% fewer[16] LERs in 2020 relative to its own performance in 1984.

Conversely, repeating this procedure with fixed effects by the year that commercial operation began (in place of reactor fixed effects) reveals zero apparent trend to support the hypothesis that newer reactors exhibit greater safety. A similar regression finds that reactors which retired prior to the year 2000[17] filed 9.4% more LERs (standard error: 3.0%), on average, compared to those which were still in operation as of January 1st, 2021. The equivalent statistic for reactors which retired between 2000 and 2020 is 8.5% (standard error: 2.4%). This suggests that LER filings are modestly associated with market exit, but the predominant effect explaining the overall trend in Figure 8 is within-reactor improvement over time.

5.2. Modeling of Licensee Event Reports

In this section, I explain the modeling choices and assumptions I make to estimate the effect of regulatory activity in licensing on the count of LERs filed by a licensee for a reactor in a given month of operation. As the outcome of interest is a count variable, I estimate the model using Poisson pseudo-maximum likelihood (Correia et al., 2019a,b). Silva and Tenreyro (2011) “confirm that the Poisson pseudo-maximum likelihood estimator is generally well behaved, even when the proportion of zeros in the sample is very large.” In my sample, 53.4% of observations (reactor-months) exhibit zero LERs.

My findings in Section 5.1 indicate that there was a large industry-wide trend towards improved safety in American nuclear power plants over the period 1984 to 2001. Because the treatment of interest varies cross-sectionally (across reactors) but does not vary longitudinally (over time), no important variation is discarded with the inclusion of time fixed effects (year and calendar month). By the same reasoning, reactor fixed effects cannot be included.

No source of quasi-experimental variation in the treatment variables are known to me at this time. Several instrumental variable research designs were considered and rejected.[18] Therefore, I take great care to control for

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[16] Margin of Error with 95% confidence: ± 0.48%

[17] Here, I do not use fixed effects for every possible year of retirement because most years have zero or one reactor retirements.

[18] Interest rates and electricity demand growth were considered as instruments for licensing review time; financing struggles and revised demand forecasts were among principal reasons why utilities delayed or temporarily suspended nuclear construction. However,

possible sources of omitted variables bias, which I discuss directly below. Thereafter, the remainder of this section is devoted to control variables that are intended to improve the precision of the model but do not counteract omitted variables bias or establish causality.

5.2.1. Omitted Variables

I consider two important sources of omitted variables bias. The first is the possibility that quality control problems in construction could lead to greater regulatory scrutiny and also worse safety performance once in operation. In principle, regulatory scrutiny could avert any such negative effect by correcting the problems. If so, we might observe zero relationship between regulatory scrutiny and operational safety despite a true causal effect of regulatory scrutiny.

For lack of any quality assurance data from the construction and commissioning process, I instead control for the cumulative experience of the architect-engineer and the constructor. These firms play important roles in the design and construction of NPPs, so it stands to reason that firms with more experience would tend to build plants with fewer flaws.

In robustness checks, I additionally control for the natural logarithms of overnight capital cost and gross lead time (refer to Appendix A for definitions and data sources). I posit that quality control problems co-vary with poor construction economics. However, lead time in construction and commissioning and the time required to receive an operating license are jointly determined, which is why I do not control for it in my preferred specification.

A second possible source of omitted variables bias I consider is the impact of state and local politics on a reactor once it is in operation. In Section 4, I find a relationship between state politics, state intervenor activity, and the time required to receive an operating license. State politics exhibit a high degree of persistence over time; for example, the coefficients of year-to-year autocorrelation are 0.9926 for state policy liberalism and 0.9234 for voter liberalism. Hence, state politics at the time of reactor licensing will necessarily be correlated with state politics over the life of the reactor's operation. If

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while these variables explain utility behavior in proceeding with the operating license review at a slower pace, they bear no theoretical connection to regulatory scrutiny, which is what the licensing review time is intended to capture. State-level liberalism was considered as an instrument for state intervenor activity, but the regressors in Table 3 have extremely weak joint relevance, well below the conventional threshold of 10 for the F statistics.

contemporary state politics have casual effects on a reactor operational safety separately from any legacy of the licensing procedure, then the estimate effect of regulatory variables from the licensing phase could be biased.

I address this issue by controlling for state politics and policy contemporary to the year of observation using the available data. I include the state policy liberalism variable for this purpose, as it reflects the ideological tenor of the political equilibrium in state government. As one example of how the current operations of state government and policy might impact nuclear power plant safety, consider the existence of the Diablo Canyon Independent Safety Committee (DCISC). Below is an excerpt from the committee's website explaining its origins:[19]

> *The concept of an independent safety committee for Diablo Canyon Power Plant arose in context of the opposition by the California Public Utilities Commission's (CPUC) Division of Ratepayer Advocates... and the then California Attorney General (John Van de Kamp) to Pacific Gas & Electric's (PG&E) request for recovery from its ratepayers for the cost of building both Diablo Canyon Nuclear Power Plant (DCPP) units. Those parties argued that billions of dollars of these costs were unreasonable and to resolve the matter in June 1988 the parties entered into a Settlement Agreement with PG&E providing for "performance based pricing." Opponents of the Settlement Agreement, such as The Utility Reform Network (TURN) argued that performance based pricing gave PG&E an incentive to maximize energy production and profits which could threaten plant safety. The CPUC recognized the safety implications of the then established performance based pricing for power produced by DCPP in its approval of Decision 88.12.083 in December 1988 which established the Diablo Canyon Independent Safety Committee (DCISC) to monitor safety at the plant.*

DSISC only possesses oversight powers. It cannot regulate PG&E's activities with regard to plant operations, an authority which the Atomic Energy Act of 1954 reserves entirely to the federal government. Nevertheless, its fact-finding activities and public meetings may heighten public scrutiny on

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[19] `https://www.dcisc.org/about/history/` Accessed 6/23/2021.

PG&E, which could influence the safety of its operations or its propensity to file Licensee Event Reports. While it would be desireable to quantify state government involvement in the operations of licensed nuclear power plants, the creation or collection of such data is beyond the scope of the current work. Therefore, I control for a state's policy liberalism as a proxy for the ideological antipathy of state policymakers towards nuclear power.

As mentioned above, Davis and Wolfram (2012) find that divestiture of ownership as part of electricity sector restructuring improves nuclear power plant output in the United States, in large part through increased reliability. Reliability and safety are likely related. Therefore, I control for whether the reactor in question has been divested from regulated ownership by a vertically-integrated utility as of the month of observation.

5.2.2. Reactor Aging

In my preferred specification, I control for a fourth degree polynomial in the age of the reactor. This degree of polynomial was selected for a mix of theoretical and empirical reasons. From a theoretical perspective, the polynomial should be of even degree to permit the model to fit a bathtub curve, which is a stylized model of failure rates in reliability engineering (Klutke et al., 2003). A bathtub curve plots the hazard rate over the operational lifetime of a facility or piece of equipment. Failures are high at the beginning of operation (when flaws in the design and manufacture are discovered), lowest in the middle years, and high again the final years as components and structures wear out.

To determine whether the polynominal should be of degree two, four, six, or higher, I successively estimated the model with an increasing number of degrees and jointly tested the statistical significance of the newly introduced coefficients. When the most recently added terms were not jointly significant, I halted the testing procedure and selected the last even degree to display statistical significance. Fifth and sixth degree terms were rejected, thus a fourth degree polynomial was selected for the model.

In the presence of time fixed effects, the coefficients on reactor age cannot be interpreted as the causal effect of aging. Reactor age in this setting is essentially a proxy for the year in which the reactor entered commercial opperation. This approach requires fewer parameters than fixed effects by year of commercial operation. Because there are only 115 reactors in the final sample, it is important to preserve parsimony of the model in the cross-sectional dimension.

5.2.3. Spillover Effects in Safety

I control for sources of spillover effects in nuclear power plant safety, i.e., patterns in safety attributable to learning, experience, or common causes at other reactors. The year fixed effects already absorb any longitudinal variation that might be explained by industry-wide learning; consequently, I do not consider it. I do construct measures of LER filings by other reactors (1) at the same site (if any), (2) of the same family, and (3) of the same sister group[20]

For reactors at the same site, I only consider LERs filed in the same month as the reactor i. This is intended to strictly capture the circumstances under which a reportable event occurs that implicates the safety of more than one reactor at the same site. For example, a loss of offsite power would impact all reactors at the same site.

I theorize that reactors of the same family are a prime source of learning spillovers. American utilities and merchant generators formed "owners' groups" through which they collaborate and exchange information with other utilities that own reactors in the same family. The original designers of the NSSS (Westinghouse, General Electric, Babcock & Wilcox, Combustion Engineering) also participate in the activities of their respective owners' groups. These entities sponsor research of common interest to the participants. While the safety of reactors within the same family are likely to be related, I doubt that such affects are transmitted instantaneously (i.e. in month t). Instead, I construct a measure of the average monthly rate of LER filing by all other reactors in the family for the current year.

I construct an equivalent measure for sister groups, which are more granular classifications than families, on the theory that certain lessons may only be transferable across reactors of greater similarity in design.

5.2.4. Technical Specifications

In general, technical specifications would be "bad controls" because, in principle, regulation should influence the design of the plant. However, one technical specification that is chosen by the utility long before the beginning of the licensing process is the size of the reactor in megawatts. It is conceivable that the size of the reactor would influence its propensity to experience

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[20] See Appendix A for sources and definitions of the reactor family and sister group typologies).

reportable events, so I control for it. Given that the outcome of interest is panel data, I control for the licensed thermal capacity in the current month, which accounts for uprates that occur over the life of the plant.

In auxiliary regressions that check for the robustness of the results, I include fixed effects by reactor family, by sister group, and a third case with two sets of fixed effects: NSSS model and type of containment. These are intended to address any lingering concerns of comparing technically unlike reactors on the basis of how much regulatory scrutiny they received. However, as mentioned above, there is a need for parsimony in the cross-sectional dimension with only 115 cross-sectional units. Hence, such fixed effects are not part of my preferred specification.

5.2.5. Treatment Variables

I consider six treatment variables, which are listed and defined in Table 4. I exclude from consideration the issuance, revision, or withdrawal of regulatory guides, because the variation in exposure to treatment is purely a function of the vintage of the plant. Two plants which proceeded through the licensing process at the same period in history were necessarily exposed to the same degree of regulatory turbulence as measured by the issuance and revision of regulatory guides. Therefore, the effect of the regulatory guides cannot be distinguished from the effect of other time-trending variables during the era when the nuclear power plants in my sample were licensed.

Treatment is assigned at the level of reactor, so I cluster the standard errors by reactor. This results in 115 clusters in the estimation of the model. The practical effect of this on statistical inference is that there are only 115 degrees of freedom available to estimate the partial association of variables that only vary cross-sectionally. Conversely, coefficients on variables which vary longitudinally as well as cross-sectionally will be estimated with much greater statistical power.

For lack of a quasi-experimental research design, I do not claim to establish causality of these treatment variables. Nevertheless, I do argue that the foregoing research design rules out many possible sources of spurious correlation. In particular, my emphasis on isolating the cross-sectional dimension of the data establishes an interpretation of the results as follows: the coefficients on these variables inform us of the partial association between (X) regulatory activity in the reactor's licensing phase and (Y) relative safety in operation at a given point in history, for reactors of the same vintage.

Short Variable Name	Substantive Meaning	Unit of Measure	Min.	Mean	Max.	S.D.
CP Review Time	time between the docketing of the application for a construction permit and the issuance of the permit	natural logarithm of months	1.14	3.05	4.66	0.62
OL Review Time	time between the docketing of the application for an operating licensing and the issuance of the license	natural logarithm of months	0.32	3.82	6.15	0.76
State Intervenor Activity (CP)	number of documents submitted by authors affiliated with the government of the state where the reactor is located, prior to the issuance of the CP	inverse hyperbolic sine of the count of documents	0	0.47	4.64	0.99
State Intervenor Activity (OL)	number of documents submitted by authors affiliated with the government of the state where the reactor is located, after the issuance of the CP but before the issuance of the OL	inverse hyperbolic sine of the count of documents	0	1.66	7.25	1.86
Amendments to the PSAR	number of amendments to the Preliminary Safety Analysis Report, submitted by the applicant in the course of the CP review	estimated count of amendments	0	21.2	88.8	17.5
Amendments to the FSAR	number of amendments to the Final Safety Analysis Report, submitted by the applicant in the course of the OL review	estimated count of amendments	0	30.8	153.5	28.9

Table 4: Treatment Variables

5.3. The Effect of Licensing Activity on Operational Safety

Table 5 displays the results of Poisson regressions in which the dependent variable is the monthly county of LERs and the independent variables consist of those described in Section 5.2. Columns (1) through (3) test treatment variables in pairs—one version of the variable for the construction permit, another for the operating license (OL)—while Column (4) tests all six treatment variables simultaneously. The headline finding is that the time required to receive an operating license is significantly related with the safety a nuclear reactor once in operation. This finding is significant both in the statistical sense and in empirical magnitude. The estimated elasticity is around -0.4: a 1% increase in the time required to receive an operating license is associated with a 0.4% reduction in the expected count of LERs filed in a given month, *ceteris paribus.*

To contextualize this elasticity, let us consider the effect in terms of empirically observed increased in OL licensing time as displayed in Figure 2. The mean months to issuance for OLs granted prior to the *Calvert Cliffs* decision was 20.9 (N=28); for OLs whose applications were docketed after the decision, the average is 81.6 (N=67). Such an increase is just shy of a quadrupling[21] in license review time and corresponds to a reduction in LERs by 42%.[22]

This finding is robust to several alternative specifications. These specifications include additional controls for overnight capital cost and gross lead time, as well as a panoply of other possible fixed effects (see Table 6). The point estimates of the elasticity of LERs with respect to OL review time under these alternative specifications range from -.27 to -.51; none of them are statistically different from -0.4.

Returning to the other results in Table 5, I will comment first on the other five treatment variables. In short, there is no apparent relationship between the review time for a construction permit, state intervenor activity, or amendments to either the PSAR or FSAR and the safety of nuclear power plant operations. The coefficients are both tiny in empirical magnitude and statistically insignificant. This raises the question of whether these features of the licensing process have any redeeming social value. For lack of a quasi-experimental research design, I cannot rule out the possibility that these

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[21] A factor of 3.9, to be precise.

[22] $3.9^{-.4} = 0.58$—i.e. 58% of the baseline rate of LER filing, or a 42% reduction.

Dependent Variable: $ln(E[LER_{it}])$

	(1)	(2)	(3)	(4)
Cross-Sectional Variables				
CP Review Time	**0.04%**			**-0.01%**
1% increase in months	(0.47)			(-0.11)
OL Review Time	**-0.36%**			**-0.41%**
1% increase in months	(-3.54)			(-3.86)
State Intervenor Activity (CP)		**0.04%**		**0.04%**
1% increase in documents		(1.05)		(1.09)
State Intervenor Activity (OL)		**-0.01%**		**-0.01%**
1% increase in documents		(-0.44)		(-0.27)
Amendments to the PSAR			**5.5%**	**4.5%**
one S.D. increase in amendments			(1.42)	(1.26)
Amendments to the FSAR			**-5.7%**	**2.1%**
one S.D. increase in amendments			(-1.13)	(0.38)
Experience of the Architect-Engineer	**0.01%**	**0.05%**	**0.05%**	**0.02%**
1% increase in cumulative experience	(0.15)	(1.46)	(1.55)	(0.53)
Experience of the Constructor	**-0.03%**	**-0.03%**	**-0.04%**	**-0.04%**
1% increase in cumulative experience	(-1.08)	(-1.00)	(-1.27)	(-1.25)
Panel Variables				
Licensed Thermal Capacity	**0.13%**	**0.09%**	**0.09%**	**0.13%**
1% increase in MW_{th}	(1.62)	(1.38)	(1.22)	(1.71)
State Policy Liberalism	**-7.3%**	**-7.5%**	**-7.2%**	**-7.9%**
one S.D. increase in state policy liberalism	(-2.82)	(-2.44)	(-2.55)	(-2.62)
Divestiture	**-17.5%**	**-19.5%**	**-17.1%**	**-16.8%**
=1 if divested from integrated utility	(-2.32)	(-2.52)	(-2.18)	(-2.09)
Investor-Owned Utility	**20.5%**	**13.8%**	**13.9%**	**20.6%**
=1 if investor-owned	(1.75)	(1.25)	(1.31)	(1.84)
Family Spillovers	**0.22%**	**0.37%**	**0.44%**	**0.28%**
1% increase in LERs of the same family	(1.09)	(1.74)	(2.11)	(1.44)
Sister Group Spillovers	**0.55%**	**0.56%**	**0.52%**	**0.54%**
1% increase … of the same sister group	(7.80)	(7.98)	(7.32)	(7.42)
Site Spillovers	**0.05%**	**0.04%**	**0.04%**	**0.05%**
1% increase in LERs at the same site	(2.18)	(1.78)	(1.78)	(2.45)
4th-Degree Polynomial of Reactor Age	✓	✓	✓	✓
Year + Month Fixed Effects	✓	✓	✓	✓
Observations	45,235	45,235	45,235	45,235

Transformed marginal effects on $E[LER_{it}]$ in **bold**. (t-statistics in parentheses.)

Table 5: Predictors of Licensee Event Reports

variables do positively contribute to safety but reactors of less safe designs are selected into treatment, cancelling out the causal effect in this observational setting.

With the above warning about causality in mind, I will speculate subjectively about likely reasons for these findings. I doubt that state governments' participation in reactor licensing contributed substantively to the safety of the reactors they opposed. A principal concern of states was emergency planning (Joppke, 1992), as in the cases of Shoreham and Seabrook; that is to say, states objected to the location of the plant on the grounds that evacuation would be infeasible. I theorize that objections to the design or operating limits of the plant flowed from this primary concern, rather than arising from a rigorous technical analysis. As I find in Table 3, ideological liberalism of state policy and the state's voters are strongly associated with state intervenor activity in the post-*Calvert Cliffs* era. This suggests that reactors faced state opposition for reasons unrelated to their safety. The present methods do not rule out the possibility of selection into treatment, but I expect that such an effect would be very slight.

Regarding amendments to the preliminary and final safety analysis reports, I consider it more credible that selection into treatment is biasing the results. Generally, the amendments to these reports occur when AEC / NRC staff determine that either (A) the report is incomplete or (B) the staff do not consider the proposed design and operating procedures to be adequate to satisfy regulations. These issues are communicated to the applicant, who then revises the report and submits the amendments. I hypothesize that amendments to these reports reflect changes in design and proposed plan of operation that were required by the NRC to bring deficient reactors up to the same level of safety as reactors whose safety analysis reports were accepted with no or few amendments. This would be consistent with a lack of an observed association.

Regarding CP review time, recall that Figure 1 exhibits comparatively less escalation in CP review times than OL review times, which are shown in Figure 2. I suspect that, to a large extent, the trends in CP review time reflect delays caused by the *Calvert Cliffs* decision and congestion in the licensing regime (i.e. the AEC having to process many applications simultaneously). While it is true that substantive safety issues were raised in construction permit hearings, in many cases the issues were generic—applicable to nuclear reactors generally (Cohen, 1979). If scrutiny in one or a few cases spilled over to impact the safety of the design of other reactors, then the present methods

Alternate Specification relative to Model (4) in Table 5	Elasticity of LER Filing with respect to OL Review Time	
	Point Estimate	Confidence Interval
additional controls for OCC and construction lead time	**-0.40**	[-0.66, -0.13]
Fixed Effects by Year of ...		
... Docketing of the CP Application	**-0.33**	[-0.54, -0.11]
... Docketing of the OL Application	**-0.27**	[-0.48, -0.07]
... Commercial Operation	**-0.51**	[-0.73, -0.28]
... Reactor Sister Group	**-0.39**	[-0.63, -0.14]
... Model of NSSS and Type of Containment Structure	**-0.30**	[-0.50, -0.09]

**instead of controls for reactor age*

Table 6: Robustness of Results to Alternative Specifications

are not equipped to detect the effect.

Furthermore, under the licensing procedures of the time, comparatively less regulatory scrutiny was applied to construction permits as the design of a plant was typically not finalized before construction began. “The [AEC/NRC] had never required the detailed technical information in construction permit proposals that it expected in operating license applications” (Walker and Wellock, 2010, pp. 62-63). This strikes me as an eminently likely plausible for the apparent importance of the duration of the OL review for the safety of the plant compared to null effects of the duration of CP review.

For reactors which have recently or in the near future plan to utilize the licensing procedures under 10 CFR 52—which allows for the issuance of a single, combined license to construct and operate a nuclear power plant—regulatory scrutiny prior to the start of construction may be more important. As no such reactors have begun operation as of the time of writing, this hypothesis cannot be explored.

5.3.1. Other Findings

I find insignificant effects of the experience of the architect-engineer and the constructor on the safety of the reactor. An elasticity of, say, -.04 implies that a doubling of cumulative experience reduces LERs by about 2.7%, which may seem negligible, except that it could add up over the course of several cumulative doublings, which is not uncommon for the most prolific firms in the nuclear industry. But the effect is not statistically significant, so I will not consider it further.

The effects of the panel variables should not be interpeted as causal. Future research using the latest difference-in-difference methods (Callaway and Sant'Anna, 2020; Goodman-Bacon, 2021) would be necessary to identify causal effects. The results in Table 5 suggest several lines of future inquiry.

The capacity of the reactor in megawatts has marginally significant and modest effects on safety. The elasticity is positive, pointing to the possibility that larger reactors may tend toward more frequent licensee event reports. This could specifically reflect the effect of uprates–increases in licensed thermal output of the reactor beyond the level permitted in the original operating license–or it may be a product of the original reactor size.

Contemporaneous state policy liberalism appears to have a statstically significant impact on the safety of nuclear power operations. The effect size–a seven to eight percentage point reduction in LERS for a one S.D. increase in state policy liberalism–is larger in magnitude than might be expected based on the formal lack of state regulatory authority concerning nuclear power plant safety.

Divestiture of the reactor from the traditional utility business model (vertical integration with cost-of-service economic regulation) and transfer of ownership to deregulated firms appears to positively improve safety. Divestiture is associated with the rate of LERs falling by approximately one-sixth. This tells a story consistent with Davis and Wolfram (2012): merchant generators respond to sharper economic incentives by improving their operations. Conversely, investor-ownership is marginally associated with worse safety performance. The magnitude of the effect is rather large but imprecisely measured and not statistically different from zero at conventional levels of significance.

Lastly, I will comment on the spillover effects. It appears that learning and experience spillovers are strongest among reactors of the same sister group. This suggests that the knowledge relevant to avoid reportable events is relatively specialized to the particular design of reactor. Family spillovers are marginal in significance and comparatively modest in magnitude, which is contrary to the hypothesis I outlined in Section 5.2 regarding reactor families and owners' groups. Site spillovers are tiny in magnitude but somewhat more precisely estimated than family spillovers. This suggests that a small number of reportable events occur in such a way to effect multiple reactors at the same site simultaneously.

6. Conclusion

In this paper, I have presented archival data quantifying various regulatory phenomena in the licensing of American nuclear power plants in the second half of the 20th century. I have shown that there exists an inflection point in the intensity of regulatory and political scrutiny paid to the nuclear industry, circa 1970. Furthermore, I have found that state activity in the licensing process is correlated with delays, especially in the 1970s and later, when there is a clear ideological correlation in terms of which states choose to intervene. These findings are consistent with an existing historical literature and support it with new quantitative evidence. In a future version of this work, I intend to re-estimate the effect of state intervention and other regulatory phenomena on time to license issuance using the methods of survival analysis.

I investigate whether regulatory scrutiny in licensing covaries with the safety of a nuclear power plant once in operation. I found that reactors which were exposed to longer review times for the issuance of an operating license exhibit lower rates of reportable safety events, a finding which is robust to a large number of controls and alternate specifications. The elasticity of this relationship is approximately -0.4; that is, a 1% increase in time spent under review for an operating licensing reduces the expected count of reportable safety events per month by 0.4%.

Cohen (1979, p. 79) argues that "CP hearings are an important forum for public participation." In her analysis of objections raised by intervenors in CP hearings, she finds that objections over certain substantive matters were related to longer review times. However, I find no statistical relationship between the safety of a reactor in operation and any attribute of the CP licensing process, be it review time, state intervenor activity, or amendments to the preliminary safety analysis report.

To speculate about why the operating license review could matter for safety while the construction permit review does not, I conjecture the following: matters of fundamental plant design were taken up in the CP review stage, whereas matters of plant operations (e.g. technical limits to operations) are addressed in the OL review stage. Per Table IV in Cohen (1979), non-process objections during CP hearings were very rarely sustained, and those which were sustained were rarely of major practical significance. The historical narrative suggests that the largest improvements to plant design were "generic" in nature; that is, they applied to all reactors at a given point time and all future reactors, such as the rules regarding emergency core cooling system. Thus, no cross-sectional variation can be leveraged to identify the safety benefit of raising and resolving such issues in licensing hearings for construction permits.

Conversely, it may be the case that the length of operating licensing review correlates with safety because the requirements written into the operating license of the reactor (such as operating procedures and technical limits to operation) are less generic and more specific to particular reactors. This hypothesis would require more granular data on the content of operating licenses to be tested.

To achieve causal identification in future research, I imagine it could be productive to analyze the substantive content of the archival records I rely on for this work. Additionally, it could be worth exploring whether the protest data employed by Fremeth et al. (2021) can serve as a relevant and exogenous instrument for regulatory activity.

Another consideration for future research is to expand the universe of safety outcomes. As the universe of events captured by licensee event reports are rarely serious incidents, these results may not appear of particularly striking significance for societal welfare. Safety outcomes such as abnormal occurrences and significant precursors could be of greater interest, although their comparative rarity makes for more challenging statistical inference.

References

Adams, G., 1981. The Iron Triangle. Transaction Publishers.

Barkan, S.E., 1979. Strategic, Tactical and Organizational Dilemmas of the Protest Movement Against Nuclear Power. Social Problems 27, 19–37.

Benson, A.G., 2021. Three Essays on the Political Economy of Nuclear Power. PhD dissertation. University of California, Irvine.

Benson, A.G., 2022. Global divergence in nuclear power plant construction: The role of political decentralization. Nuclear Technology 208, 947–

989. URL: `https://doi.org/10.1080/00295450.2021.1991762`, doi:`10.1080/00295450.2021.1991762`.

Berndt, E., Aldrich, D.P., 2016. Power to the people or regulatory ratcheting? explaining the success (or failure) of attempts to site commercial us nuclear power plants: 1954–1996. International Journal of Energy Research 40, 903–923.

Berry, W.D., Ringquist, E.J., Fording, R.C., Hanson, R.L., 1998. Measuring Citizen and Government Ideology in the American States, 1960-93. American Journal of Political Science , 327–348.

Berthélemy, M., Escobar Rangel, L., 2015. Nuclear Reactors' Construction Costs: the role of lead-time, standardization and technological progress. Energy Policy 82, 118–130.

Bupp, I.C., Derian, J.C., 1978. Light water: How the Nuclear Dream Dissolved. Basic Books, Inc.

Callaway, B., Sant'Anna, P.H., 2020. Difference-in-differences with multiple time periods. Journal of Econometrics .

Caughey, D., Warshaw, C., 2015. The Dynamics of State Policy Liberalism, 1936-2014. American Journal of Political Science doi:`doi:10.1111/ajps.12219`.

Cohen, B.L., 1990. The Nuclear Energy Option: an alternative for the 90s. Springer.

Cohen, L., 1979. Innovation and Atomic Energy: nuclear power regulation, 1966-present. Law & Contemporary Problems 43, 67.

Cohen, L., McCubbins, M., Rosenbluth, F., 1995. The Politics of Nuclear Power in Japan and the United States, in: Cowhey, P.F., McCubbins, M. (Eds.), Structure and Policy in Japan and the United States. Cambridge University Press, pp. 177–202.

Correia, S., Guimarães, P., Zylkin, T., 2019a. ppmlhdfe: fast Poisson estimation with high-dimensional fixed effects `https://arxiv.org/abs/1903.01690`.

Correia, S., Guimarães, P., Zylkin, T., 2019b. Verifying the existence of maximum likelihood estimates for generalized linear models `https://arxiv.org/abs/1903.01633`.

Davis, L.W., Wolfram, C., 2012. Deregulation, consolidation, and efficiency: evidence from us nuclear power. American Economic Journal: Applied Economics 4, 194–225.

Eash-Gates, P., Klemun, M.M., Kavlak, G., McNerney, J., Buongiorno, J., Trancik, J.E., 2020. Sources of Cost Overrun in Nuclear Power Plant Construction Call for a New Approach to Engineering Design. Joule 4, 2348–2373.

Ford, D.F., Kendall, H.W., 1972. Nuclear Safety. Environment: Science and Policy for Sustainable Development 14, 2–48.

Fremeth, A.R., Holburn, G.L., Piazza, A., 2021. Activist Protest Spillovers into the Regulatory Domain: theory and evidence from the US nuclear power generation industry. Organization Science .

Gavrilas, M., Hejzlar, P., Todreas, N.E., Shatilla, Y., 1995. Safety Features of Operating Light Water Reactors of Western Design. CRC Press.

Gogan, K., Ingersoll, E., Foss, A., Herter, J., 2018. The eti nuclear cost drivers project: Summary report `https://www.eti.co.uk/library/the-eti-nuclear-cost-drivers-project-summary-report`.

Goodman-Bacon, A., 2021. Difference-in-differences with variation in treatment timing. Journal of Econometrics .

Green, H.P., 1973. Public Participation in Nuclear Power Plant Licensing: the Great Delusion. William & Mary Law Review 15, 503.

Höhle, M., Held, L., 2006. Bayesian Estimation of the Size of a Population. Discussion Paper, No. 499, `http://hdl.handle.net/10419/30999`.

Hultman, N., Koomey, J., 2013. Three Mile Island: the driver of US nuclear power's decline? Bulletin of the Atomic Scientists 69, 63–70.

Informational System for Occupation Exposure, 2000. List of BWR and CANDU Sister Unit Groups. `https://`

`isoe-network.net/publications/pub-resources/pub-info-sheet/etc-information-sheets/205-etc-24.html`.

Informational System for Occupation Exposure, 2010. PWR Outage Collective Dose: Analisys per Sister Unit Group for the 2002-2007 Period. `https://isoe-network.net/docs/publications/isoe-resources/isoe-information-sheets/etc-information-sheets/1497-etc-52.html`.

Joppke, C., 1992. Decentralization of control in us nuclear energy policy. Political Science Quarterly 107, 709–725.

Joppke, C., 1993. Mobilizing against Nuclear Energy: a comparison of Germany and the United States. University of California Press.

Jordan, M.P., Grossmann, M., 2016. The Correlates of State Policy Project v1.14. `http://ippsr.msu.edu/public-policy/correlates-state-policy`.

Klutke, G.A., Kiessler, P.C., Wortman, M.A., 2003. A Critical Look at the Bathtub Curve. IEEE Transactions on Reliability 52, 125–129.

Komanoff, C., 1981. Power Plant Cost Escalation: nuclear and coal capital costs, regulation, and economics. Van Norstrand Reinhold Company.

Koomey, J., Hultman, N.E., 2007. A reactor-level analysis of busbar costs for US nuclear plants, 1970–2005. Energy Policy 35, 5630–5642.

Lovins, A.B., 1976. Energy Strategy: The Road Not Taken? Foreign Affairs 55, 65.

Lyons, R.D., 1971. A.E.C. Shifts Role to Protect Public. New York Times October 21.

Lyons, R.D., 1972. Nuclear Experts Share Doubts on Power Plant Safety. New York Times March 12.

Nuclear Engineering International, 2012. World Nuclear Industry Handbook.

Paik, S., Schriver, W.R., 1980. The Effect of Increased Regulation on Capital Costs and Manual Labor Requirements of Nuclear Power Plants. The Engineering Economist 26, 223–244.

Palfrey, J.G., 1974. Energy and the Environment: the special case of nuclear power. Columbia Law Review 74, 1375–1409.

Portugal-Pereira, J., Ferreira, P., Cunha, J., Szklo, A., Schaeffer, R., Araújo, M., 2018. Better late than never, but never late is better: risk assessment of nuclear power construction projects. Energy Policy 120, 158–166.

Quirk, J., Terasawa, K., 1981. Nuclear Regulation: an historical perspective. Natural Resources Journal 21, 833–855.

Rodriguez, D.B., Weingast, B.R., 2015. The 'Reformation of Administrative Law' Revisited. The Journal of Law, Economics, and Organization 31, 782–807.

Roe, D., 1984. Dynamos and Virgins. Random House.

Schumacher, E.F., 1973. Small is Beautiful: a study of economics as if people mattered. Blond & Briggs.

Silva, J.S., Tenreyro, S., 2011. Further simulation evidence on the performance of the poisson pseudo-maximum likelihood estimator. Economics Letters 112, 220–222.

Stewart, W.R., Gregory, J., Shirvan, K., 2022. Construction duration estimation for advanced nuclear power plants. Working Paper `doi:10.31219/osf.io/j45aw`.

Surrey, J., Huggett, C., 1976. Opposition to nuclear power: a review of international experience. Energy Policy 4, 286–307.

Temples, J.R., 1980. The Politics of Nuclear Power: a subgovernment in transition. Political Science Quarterly 95, 239–260.

United Engineers and Constructors, 1984. Phase VI Update (1983) report for the Energy Economic Data Base Program. Prepared for U.S. Department of Energy. `https://www.osti.gov/servlets/purl/6504693/`.

U.S. Nuclear Regulatory Commission, 2013. ADAMS Application Programming Interface (API): Developer's Guide. `https://www.nrc.gov/site-help/developers/wba-api-developer-guide.pdf` (accessed 3/1/2021).

Walker, J.S., Wellock, T.R., 2010. A short history of nuclear regulation, 1946–2009. U.S. Nuclear Regulatory Commission. NUREG/BR-0175, Revision 2.

Wellock, T.R., 1998. Critical Masses: Opposition to Nuclear Power in California, 1958-1978. University of Wisconsin Press.

Wellock, T.R., 2012. Engineering Uncertainty and Bureaucratic Crisis at the Atomic Energy Commission, 1964-1973. Technology and Culture 53, 846–884.

Appendix A. Data Sources on Nuclear Power plants

This paper relies on the global database of nuclear power plants assembled for my dissertation (Benson, 2021). The database draws primarily on the Power Reactor Information System (PRIS) of the International Atomic Energy Agency (IAEA), supplemented by original research and appending dataset generated by other scholars. The data, excepting any data which is subject to IAEA data sharing restrictions, have been made available at `https://github.com/a-g-benson/Global-NPP-Database`. Here, I briefly discuss the data sources and variables relevant to the current work. Further detail, such as the data cleaning procedures, are available in Benson (2021) and Benson (2022).

Appendix A.1. Construction Economics

Multi-Unit Construction: When multiple reactors are reported to have begun construction in tandem at a site, it atypical for those reactors to be completed by the same date. This reflects the fact that NPP construction management usually economizes on equipment and labor by not performing the same tasks for both reactors at the same time. Thus, the second reactor is liable to finish, approximately, one year after the first, the third one year after the second, and so on. This pattern can be almost perfectly predicted by the number assigned each to unit. I code a variable M_i that ranks reactors at the same site which share a construction start date.

Gross Lead Time: I compute gross lead time as the difference in days between the construction start date and the date of commercial operation.

Net Lead Time: I subtract the number of days during which a reactor's construction was suspended (if any) from the gross lead time to generate the net lead time.

Overnight Capital Cost: I append to my database the overnight capital cost (OCC) data of Portugal-Pereira et al. (2018), which is in PPP-adjusted US dollars, inflation-adjusted to the year 2010.

Architect-Engineer: The architect-engineer (AE) is the firm which was responsible for the design of the overall plant, unifying the NSSS with the steam turbines, generator, other major infrastructure, and auxiliary buildings. This information is not provided by PRIS. Instead, I compiled the data provided by Berthélemy and Escobar Rangel (2015) and Gavrilas et al. (1995), which provide coverage for light water reactors of Western design.

Remaining gaps were filled in with data from the World Nuclear Industry Handbook (NEI, 2012).

Constructor: The constructor is the firm responsible for day-to-day management and supervision of construction at the site, including the hiring and managing of many subcontractors for specific tasks. In some cases, one firm serves as both AE and constructor.

Appendix A.2. Reactor Typology

Reactor Family: I use the term "family" to classify reactors that have a shared evolutionary heritage. The largest family is the Westinghouse family, which includes not only PWRs designed by Westinghouse, but those designed by firms which licensed Westinghouse's intellectual property, notably Framatome, Siemens, and Mitsubishi. The identification of families was based explicitly on the "family trees" provided in Gavrilas et al. (1995) for Western light water reactors.

Sister Group: I draw on the "sister unit group" classifications of the Information System on Occupational Exposure, a project of the OCED Nuclear Energy Agency (ISOE, 2000; ISOE, 2010). Where possible, I extend these classifications to reactors which are absent from the aforementioned sources on account of retirement or abandoned construction. These classifications occupy a middle ground of granularity between family and model. They are more specific than family in that sister groups are based on the firm that designed the NSSS, whereas family is based on the firm that originated the intellectual property for the NSSS. In additoin, sister groups also specify the vintage of the plant (e.g. BWR-1, BWR-2, BWR-3, and so on); for PWRs, they further specify the number of primary coolant loops.

Containment Design: For American PWRs, the containment structure is classified according to one of the following: large dry, subatomspheric, and ice condenser. For BWRs, containments are either Mark I, Mark II, or Mark III. These classifications are sourced primarily from IAEA PRIS; omissions were supplemented by original research.

Appendix A.3. Reactor Ownership

In Benson (2021), I supplemented information from IAEA PRIS on the current plant owner to identify the original owner at the time of construction. I also researched ownership shares for reactors with multiple owners. I code a reactor as investor-owned so long as a majority of its ownership is private, and not public.

Davis and Wolfram (2012) identifies the dates of NPP divestiture from investor-owned utilities. I cross-checked their dates of unbundling with contemporary reporting in industry periodicals and mass-market newspapers and made minor corrections. For the dates of introduction of wholesale competition, I referenced the websites of American RTOs and ISOs, which usually provided historical timelines.

Appendix B. Regulatory Data from the United States

Appendix B.1. Regulatory Guides

The U.S. Nuclear Regulatory Commission (NRC) provides the following descriptions of its regulatory guides on its website:[23]

> *The Regulatory Guide series provides guidance to licensees and applicants on implementing specific parts of the NRC's regulations, techniques used by the NRC staff in evaluating specific problems or postulated accidents, and data needed by the staff in its review of applications for permits or licenses.*

The first regulatory guides were introduced in November of 1970 in order to help applicants better navigate the increasing thicket of regulations and documentation required by the Atomic Energy Commission. Over the subsequent decades, a total of 496 regulatory guides have been published, 558 revisions have been issued, and 144 have been withdrawn (as of December 2020).

The regulatory guides are not in and of themselves binding regulations; those are found within Title 10 of the Code of Federal Regulations. I use regulatory guides over actual regulations for two reasons. The first consideration is data availability. The CFR is only digitized from 1996 onward; the Federal Register (in which changes to the CFR are announced for the purposes of public notice) is only digitized from 1994 onwards. By contrast, the complete universe of regulatory guides—including all past versions and their month of issuance—is digitized and publicly available from the NRC's website.

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[23] `https://www.nrc.gov/reading-rm/doc-collections/reg-guides/index.html` (accessed 5/27/21)

“Format”
“Application”
“Terms and Definitions”
“Guidance for the Preparation of Applications for”
“Preparation of ... Reports for”
“Format and Content of ... Safety Analysis Reports”

Table B.7: Search Terms to Identify Regulatory Guides of a Clerical Nature

The second consideration in favor of regulatory guides concerns the ability to discriminate between regulatory guides with significance to the design and construction of nuclear power plants, items relating to operations, or not related to nuclear power plants at all. The AEC (NRC) regulated (regulates) several other aspects of the nuclear fuel cycle and other industries using radioactive material, so it is important for any measure of regulatory activity to avoid inclusion of these other industries. I draw on the work of United Engineers and Constructors (1984) who classified every regulatory guide in this manner. The regulatory guides are numbered and their subject matter does not vary over time, so I can safely rely on these classifications even in cases where revisions to the guide occur after 1983. I extend their work by manually classifying regulatory guides which were introduced after 1983. I further refine the scope of the Regulatory Guide data by dropping from consideration guides concerning regulatory “paperwork” as opposed to regulatory substance. In particular, I drop guides that contain any of the terms listed in Table B.7.

The effort required to collect and categorize revisions to Title 10 of the Code of Federal Regulations in an equivalent manner are beyond the scope of the present work.

Appendix B.2. Safety Analysis Reports

10 CFR 50.34 requires that “[e]ach application for a construction permit shall include a preliminary safety analysis report” (PSAR) and “[e]ach application for an operating license shall include a final safety analysis report” (FSAR). These reports describe the design of the facility, lay out a plan for quality assurance in material and equipment, propose operating limits, and analyze the safety of the facility. The primary audience for these reports were (are) the AEC (NRC) staff, who review them for completeness and substantive compliance with safety regulations. Inadequately detailed reports were

a sufficiently routine problem that it stimulated the development of several of the earliest regulatory guides.

I collected bibliographic metadata from the the NRC's digital library ADAMS[24] using the NRC's Application Programming Interface (NRC, 2013) and Windows PowerShell. I ran one search for each reactor according to its docket number, a unique and consistent identifier assigned by the AEC/NRC at the time of the application for a construction permit. I restrict the search to all documents whose title makes reference to a PSAR or FSAR.

In most cases, PSARs and FSARs were amended by the applicants dozens of times before being accepted by the AEC/NRC staff, although there tremendous cross-sectional variability, as seen in Figures 6 and 6. Each instance of an amendment is numbered, making it feasible to identify the total number of amendments to the PSAR and to the FSAR for each reactor. Below I detail the procedures to clean the raw data and produce the best estimate of the total number of amendments.

Amendment numbers appear in the titles of documents related to PSARs and FSARs, so I extract the numbers regular expressions. Some amendments are referred to in the title of multiple documents, in which cases I drop duplicates of the same amendment number. Other amendments are missing from the bibliographic record, but their existence can be inferred from the survival of amendments with numbers greater and lower than the missing number. To address the possibility that the numerically greatest amendment is not observed, I estimate the expected number of total amendments according to the Bayesian solution to the German Tank Problem (Höhle and Held, 2006):

$$E[N|m] = \frac{k-1}{k-2} \cdot (m-1) \text{ for } k \geq 2 \tag{B.1}$$

where N is the total number in the population, m is the highest observed number in the sample, and k is the number of unique values observed.

In most cases, the numbering of amendments for the PSAR and FSAR are separate; that is to say, the first amendment to the FSAR is numbered 1. However, in some cases, the enumeration of FSAR amendments follows from where the enumeration of PSARs left off. I discriminate between these two cases by comparing the lowest observed FSAR amendment number to the highest observed PSAR amendment number. In the case where FSAR

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[24] `https://adams.nrc.gov/wba/`

amendments continue enumeration from PSAR amendments, the estimate $E[N|m]$ for the PSARs is subtracted from the observed value of m for the FSARs.

During the 1990s, the NRC introduced a formal requirement for "updated" FSARs (UFSARs) which reflect changes to the technical specifications of plant over the course of its operational history. Prior to the introduction of UFSARs, FSARs were intermittently updated at some plants but not others. Because my analysis is limited to the licensing procedures, I exclude from consideration all bibliographic results dated after the issuance of the operating licensing of the reactor. However, I do provide code for downloading UFSARs in the online repository, for the benefit of other researchers.

Appendix B.3. Licensee Event Reports

10 CFR 50.73 requires that licensees "submit a Licensee Event Report (LER) for any event of the type described in this paragraph within 60 days after the discovery of the event." Reportable events include plant operation in violation of technical specifications, the discovery of degraded safety systems, unplanned reactor trips and scrams, failure of safety systems to operate as intended, radioactive releases beyond regulated limits, and similar safety issues.

As with safety analysis reports, I collect bibliographic data on all LERs using the NRC's API for ADAMS and Windows PowerShell. LERs are matched to individual reactors by docket number. The date of the document is taken as the best approximation of the date on which the event occurred. 10 CFR 50.73 allows up to sixty days of delay between the event and the submission of the report to allow for the writing of the report. Retrieval of the actual date of the event would be impractical due to the need to optically scan tens of thousands of PDFs; furthermore, machine-readable PDFs of LERs do not exist prior to the NRC's transition to digital record-keeping on November 1st, 1999. Such LERs are stored in microfiche format.

The reporting requirements of 10 CFR 50.73 entered into effect on January 1st, 1984 (48 FR 33850) and superseded previous requirements, which were specified on a case-by-case basis in the operating licenses of each reactor. Thus, cross-reactor comparisons prior to 1984 should be treated with caution. In the pre-1984 era, a greater number of LERs may reflect more incidents, or it may reflect more stringent reporting requirements. From 1984 onwards, the requirements were standardized across plants.

On inspection, I find an unusually high number of LERs in January of 1984, as compared with other months in 1984 and January of other 1985 through 1989. Given the lag between when events occur and when they are reported, I suspect this reflects transitory adjustment issues from the old LER reporting requirements to the new LER reporting requirements. Therefore, I exclude January 1984 from all regression analyses. However, for balance in the number of months across all years, I retain it for the purposes of constructing certain graphs.

While the longitudinal variation in LERs filing rates is not of primary interest in this work, I report here a survey of announcements in the Federal Register (FR) regarding all revisions to 10 CFR 50.73 in case it is of interest to the reader or other researchers. An exhaustive list of such revisions is provided on the NRC's website,[25] which I double-checked using the search function on `federalregister.gov`. The survey is presented in the form of Table B.8. Overall, most revisions are not substantive or so modest in effect as to not meaningfully contribute to the tremendous decline in the rate of LER filing reported in Section 5.1. However, a few revisions do merit comment.

The revision introduced at 56 FR 23473 implies the possibility of non-standardization in reporting requirements regarding airborne and liquid radioactive releases due to the introduce of an alternative set of criteria for some but not all reactors. However, this arrangement was effectively repealed less than 2 years later by the rule changed announced at 58 FR 50689.

The revision of 10 CFR 50.73 promulgated at 65 FR 63787 are the most extensive of any I reviewed. The effective date for these changes was January 23rd, 2001. The nature of these changes suggest one possible account for the historically low rate of LER filings in the years 2001 to the present. However, Figure 8 clearly shows that the rate of LER filing was trending sharply downwards in years immediately prior to 2001. There is no observable discontinuity around the threshold of January 2001. Therefore, I do not consider it likely that these change account for much of the long-term trends in LERs.

69 FR 18803 is provided by the NRC at the bottom of a webpage that displays the current text of 10 CFR 50.73 and lists all relevant citations in

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[25] `https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0073.html` (accessed 7/8/2021)

the Federal Register which announce final rules modifying it.[26] However, upon reviewing 69 FR 18803, I found no reference to 10 CFR 50.73 on that page or nearby pages. While the NRC does make announcements elsewhere within the April 9th issue of the Federal Register (69 CFR 18988), none of these make reference to 10 CFR 50.73. A search of the Federal Register using `federalregister.gov` returns no results that plausibly explain this seemingly erroneous reference. I therefore disregard it.

Fortuitously, the aforementioned search did return a result that is closely related to 10 CFR 50.73. In 69 FR 68047, the NRC announced a final rule creating 10 CFR 50.69, which gives licensees the option to classify their systems, structures, and components (SSCs) according to a scheme of four categories related to their safety significance. Provided that the NRC accepts the licensee's classifications, then non-safety-significant SSCs belonging to two of these four categories become exempt from many reporting requirements, including those of 10 CFR 50.69. *Prima facie*, it would be unsurprising if LER filing rates had declined after this rule was finalized. However, LER filing rates have remained remarkably stable in the years after 2004, at levels comparable to those from 2001 to 2004. Therefore, the significance of this rule change appears to be minimal relative to the massive decline during the late 20th century.

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[26] *ibid.*

Reference	Date	Description
48 FR 33858	7/26/1983	introduces 10 CFR §50.73, with a reporting deadline of 30 days
49 FR 47824	12/7/1984	incorporates by reference IEEE Standard 803-1983, which provides for common definitions of systems, structures, and components
51 FR 40310	11/6/1986	makes minor revisions in wording for administrative provisions; no substantive changes
56 FR 23473	5/21/1991	introduces alternate requirements for airborne and liquid radioactive releases for certain licensees
56 FR 61352	12/3/1991	corrects typos
57 FR 41381	9/10/1992	modestly broadens criteria for when the activation of an engineered safety feature need not be reported
58 FR 67661	12/22/1993	eliminates of alternate requirements for airborne and liquid radioactive releases for certain licensees, thereby returning to universal requirements
59 FR 50689	10/5/1994	changes address for submitting LERs (NRC moved headquarters)
63 FR 50480	9/22/1998	removes references to ”utility” (to be inclusive of merchant generators)
65 FR 63787	10/25/2000	revises reporting deadline to 60 days; allows that invalid actuation of certain engineered safety features may be reported by phone instead of in writing; seeks to reduce administrative burden; introduces new reporting requirements for degraded components; makes editorial revisions to language of existing substantive requirements
69 FR 18803	4/9/2004	erroneous reference given by the NRC; see text for explanation
69 FR 68047	11/22/2004	introduces 10 CFR §50.69, which gives licensees the option to classify their systems, structures, and components according to a scheme of four categories, of which two thereby become exempt from 10 CFR §50.73 (and other reporting requirements)
72 FR 49502	8/28/2007	extends requirements of 10 CFR §50.73 to holders of combined construction and operating licenses (COLs)

Table B.8: List of Revisions to 10 CFR §50.73

Appendix B.4. Documents Filed in Licensing Proceedings by State and County Governments

I collected bibliographic metadata on all documents in ADAMS whose "author affiliation" field corresponds to the government of the state or county where the reactor is located. Documents are treated as related to the construction permit proceedings if they are dated prior to the issuance of the construction permit; they are treated as related to the operating licensing proceedings if they are dated after the issuance of the construction permit but before the issuance of the operating license. Documents filed after the issuance of the operating license are disregarded in my analysis but available in the raw data.

Appendix C. U.S. State-Level Data

My primary source of state-level data is the Correlates of State Policy Project at Michigan State University (Jordan and Grossmann, 2016), which aggregates the data of several dozen studies into a single panel (state-by-year) dataset. Below I list the key variables upon which I rely and credit their original authors.

Appendix C.1. State Policy Liberalism

Caughey and Warshaw (2015) estimate an annual measure of the ideological lean of state policies from a latent-variable model of 148 policies for each state over the years 1936 to 2014. The authors gathered data on the content and nature of state law on policies ranging from criminal justice to labor law to environmental protection, among several others. The measure is signed such that positive values represent liberalism and negative scores represent conservatism. The measure is scaled by standard deviations.

Appendix C.2. State Voter Liberalism

Berry et al. (1998) constructed a measure of the ideology of the citizens in each state. The latest version of the dataset covers the years 1960 to 2016.[27]

Because it relies on voting patterns, I refer to this variable instead as measure of voter ideology, as it cannot capture the preferences of citizens

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[27] Available at `https://rcfording.com/state-ideology-data/`. I rely on the version included with the Correlates of State Policy Project by Jordan and Grossmann (2016), which covers 1960 to 2013.

who do not vote. For my purposes, this is not a concern, as I do not expect that the opinions of non-voters would be material to any of my analyses.

The measure infers voter ideology from the ratings given to their Congressional representatives by ideological interest groups, specifically Americans for Democratic Action (ADA) and the AFL-CIO's Committee on Political Education (COPE). Voters are assumed to have ideological preferences closer to the candidate they voted for than the other candidate (only major party candidates are considered). The vote shares received by each candidate are used to construct a weighted average of the scores of the two major party candidates. For states with more than one seat in the House of Representatives, all districts are averaged together to generate a score for the state. For further details, consult Berry et al. (1998).