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Three Essays on the Political Economy of Nuclear Power

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Three Essays on the Political Economy of Nuclear Power

DISSERTATION

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DOCTOR OF PHILOSOPHY

in Economics–Public Choice

by

Andrew Glen Benson

Dissertation Committee:
Professor Emerita Cohen, Chair
Professor Emeritus Glazer
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DEDICATION

To my father,
whose long career in the nuclear industry has been a source of insight.

To my mother,
whose example I follow in attaining a doctorate.

To my brother,
who never ceases to cheer on my accomplishments.

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ABSTRACT OF THE DISSERTATION

Three Essays on the Political Economy of Nuclear Power

By

Andrew Glen Benson

Doctor of Philosophy in Economics–Public Choice

University of California, Irvine, 2021

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This dissertation encompasses three works on nuclear power plants (NPPs). A theme common to all chapters is the question of why nuclear power has failed to achieve the success envisioned by its proponents, particularly when that success has been achieved at certain times and in certain places yet failed to continue into the present day or disseminate globally. I address my research questions with a theoretical framework informed by the study of political economy, which I argue is necessary to understand this politically-charged subject.

In Chapter 1, I study lead time—the duration of construction and commissioning—which is an important determinant of the capital cost of NPPs. For an industry dominated by a handful of multinational firms, the degree of cross-national variation is surprising. NPP lead times have historically trended upwards over time in Western nations, and yet they are comparatively quick and stable in East Asia. I theorize that the institutional capacity and autonomy of subnational governments can partially explain these patterns in the data. Having assembled a novel dataset on the design specifications of the global population of NPPs, I empirically document a positive association between political decentralization and NPP lead time that is not explained by observed cross-country differences in NPP design. The results are suggestive of the hypothesis that political decentralization creates conditions that slow NPP construction for non-technical reasons. However, the findings are not robust

to certain robustness checks and fail to rule out the possibility that unobserved differences in design explain this association.

In Chapter 2, I study the operational reliability of NPPs, which has globally trended upwards since the 1970s. Previously, Davis and Wolfram (2012) showed that the transfer of NPP ownership from vertically-integrated utilities under cost-of-service regulation to independent power producers operating in competitive wholesale electricity markets substantively contributed to the upward trend in reliability in the United States. However, international data reveal persistent and large cross-country differences in NPP reliability. Notably, NPPs in the United States substantially outperform their peers in other highly developed economies, even those with earlier and more comprehensive liberalizations of their electricity sector. The present work extends the analysis of Davis and Wolfram (2012) to nearly the global population of NPPs and encompasses a more diverse set of ownership structures and regulatory frameworks under which countries restructured their electricity markets beginning in the 1990's. I find the effects of restructuring on NPP reliability vary widely by country, with the clearest successes in the United States and Canada, but muted or even negative impacts elsewhere.

Chapter 3 focuses specifically on the United States and makes three contributions. First, I present novel empirical evidence to support prior qualitative and historical work which characterizes the regulatory environment for NPPs in the United States as having dramatically escalated, beginning circa 1970. Second, I find a positive partial association between certain regulatory phenomena and the time required for a reactor to receive a license and begin commercial operation, subject to several controls. Among other results, I show that state intervention in reactor licensing (which is formally solely under federal purview) is positively associated with longer licensing duration, specifically in the 1970s but not earlier. Third, I ask whether the licensing hold-up achieved its stated goal of increased reactor safety. While my methods lack causal identification, I show that reactors which took longer to receive an operating license exhibit a noticeably lower rate of common, low-level safety incidents in comparison to other reactors of the same age and technical characteristics.

Finally, in Appendix A, I present a novel dataset of NPPs that encompasses technical, economic, political, regulatory, and geographical characteristics of the global population of commercial nuclear power plants. I combined a large number of publicly available datasets with extensive original data collection and cleaning. My database is the backbone of this dissertation and should be of use for many possible future research projects. Except for certain restricted-access data provided by the International Atomic Energy Agency, I have made the data available for public dissemination at `https://github.com/a-g-benson/Global-NPP-Database`.

Chapter 1

Global Divergence in Nuclear Power Plant Construction: the role of political decentralization

It is a stylized fact that the capital costs of nuclear power plants (NPPs) have historically trended upwards in Western developed nations. Some scholars have characterized this as "negative learning-by-doing" (Grubler, 2010; Sovacool et al., 2014b). This trend is often contrasted sharply with the steady downward trajectory of the cost of other electric generation technologies ("positive" learning-by-doing), particularly photovoltaic solar panels, wind turbines, and gas combustion turbines (Rubin et al., 2015). Budget overruns and schedule slippage in the construction of the AP1000 in the United States and the EPR in Europe indicate that the nuclear industry's economic woes have yet to be properly addressed. The problematic economics of NPP construction are representative of "megaproject syndrome" (Flyvbjerg et al., 2003), a theory which applies to massive infrastructure projects broadly, such as airports, urban public transit, high-speed rail, hydroelectric dams, and sports venues.

Academics and industry observers have offered numerous explanations for the root causes of the cost problem for the nuclear industry: construction project mismanagement (Shyloski, 2017), evolution in the political environment and regulatory regime (Komanoff, 1981), lack of standardization in design (Csereklyei et al., 2016), reliance on immature or incomplete designs before beginning construction (Gogan et al., 2018), diseconomies of scale (Adams, 1996), and added complexities in design arising from innovation in nuclear safety (Berthélemy and Escobar Rangel, 2015). However, outside the West, historic trajectories and recent results in NPP construction suggest that an upward cost trend is not inevitable and lower costs are possible (Lovering et al., 2016), although this interpretation and the credibility of the underlying data are disputed (Koomey et al., 2017; Gilbert et al., 2017). The present work wades into this fierce debate with two primary contributions: (1) novel, rich data on the design specifications of NPPs (see Appendix A), and (2) a quantitative analysis that connects the study of the nuclear industry to the literature of institutional political economy.

Previous studies of this industry have been haunted by the specter of omitted variable bias: simple cross-country and time-trend analyses of NPP construction outcomes are not necessarily valid for causal inference given that the technical characteristics of nuclear power plants vary across countries and over time (Lovering et al., 2017). The present work is the first of its kind (to the author's knowledge) to incorporate detailed data that "look inside" a nuclear reactor. These include such variables as the operating temperature and pressure of the primary coolant, the number of primary coolant loops, the size of the reactor pressure vessel, the choice of cooling technology, and the design of the containment structure. Previous work has been largely limited to power output in megawatts and categorical classifications of the make and model of reactor. Unfortunately, due to the terms under which I accessed this data from IAEA, much of the underlying data cannot be publicly made available for replication. Nevertheless, all of the analyses I present herein—except one—can be replicated with the data I have provided in the online data appendix.

In seeking to explain the high degree of cross-national variation, I observe the long and storied history local opposition as a factor in the siting, regulation, construction, and cancellation of NPPs. I argue that the political economy of nuclear power is characterized by locally concentrated risks and diffuse national (and global) benefits, in an inversion of the classic problem formalized by Olson (1965). Hence, NPPs are expected to face greater regulatory hurdles and political constraints in countries whose subnational governments have greater autonomy and institutional capacity. This generates a suite of hypotheses regarding how the degree of federalism or regional autonomy ("decentralization," for brevity) influences the design characteristics of nuclear reactors, the speed of their construction, and the industry's ability to improve upon past performance through learning.

To perform the quantitative analysis, I combine the technical data on reactors with economic and political data regarding the nation in which the NPP was constructed, including democracy, regime change, decentralization, national level of economic development, and utility ownership (public or private). In the present work, I take lead time (LT) as the sole outcome of interest, due to data availability and quality issues associated with overnight capital cost (OCC). The headline findings of the analysis are as follows:

I find no significant association between a nation's political conditions and the expected lead time of its NPPs given their observed design specifications. In other words, highly decentralized countries do not systematically choose design characteristics of NPPs that would tend toward longer lead times.

Instead, I find a statistically significant and economically substantive association between decentralization and actual lead time, when holding design characteristics constant. The estimated effects imply that one standard-deviation increase in a nation's political decentralization is associated with approximately a 9.5% increase in lead time, which amounts to 8 months of additional lead time for the typical 1 gigawatt reactor.

However, this second finding is not robust to the strictest possible test, whereby I only compare reactors of identical models through the inclusion of fixed effects. This analysis fails to reject the null hypothesis of no association between LT and decentralization. One possibility is that unobserved technical differences in design may explain the empirically observed raw correlation between LT and decentralization. Alternatively, because many models of reactors are observed in only one country or a few similar countries, high reliance on fixed effects may sap the data of statistical power. Richer data on technical specifications—particularly those related to safety systems—are needed to resolve this question.

My final finding relates to the theory of "megaproject syndrome" (Flyvbjerg et al., 2002). As previous research has shown, larger NPPs take longer to build and I replicate that result here. I extend this finding in two ways: I generate a more comprehensive measure of scale and project complexity, namely an NPP's expected lead time conditional on its size and design specifications, and validate it as having predictive power in explaining observed lead time. Then, I show that expected lead time does not correlate with observed lead times in a one-to-one relationship in all countries. In particular, I find that East Asian nations—Japan, South Korea, mainland China, and Taiwan—have historically completed construction of their NPPs much faster than would otherwise have been expected on account of the "megaprojectiness" of their NPPs. However, I find no evidence for the hypothesis that decentralization mediates the relationship between NPP scale and lead time.

The outline of this chapter is as follows. Section 1.1 reviews the literature and elaborates the theory that motivates the empirical analysis. Section 1.2 summarizes the dataset assembled for this paper. Section 1.3 formally lays out the econometric specifications. Section 1.4 presents the results. Section 1.5 discusses the results and proposes directions for future research. The data sources, cleaning, coding procedures, and restrictions on the availability of the data are detailed in Appendix A. Appendix B addresses several methodological issues and assumptions.

1.1 Background, Theory, and Prior Work

1.1.1 Measurement of Capital Cost in the Electricity Sector

The two most widely studied outcomes in the literature on NPP construction are overnight capital cost (OCC) and lead time (LT).

OCC consists of all outlays on materials, manufactured components, construction equipment, construction labor, engineering services, land, and permitting fees. These are what economists call accounting costs. The designation “overnight" refers to the hypothetical case of a power plant constructed from start to finish over the course of a single night. Effectively no interest would accumulate during construction. While not a complete measure of capital cost, OCC enables comparisons of the capital costs of different NPPs independently of financing parameters, which can vary due to macroeconomic conditions, government policies to subsidize the cost of capital, and other factors outside the control of the firm building the plant.

In this chapter, I use LT to denote the length of time between initiation of major construction activities and the start of commercial operation. By convention in the nuclear industry, the initiation of major construction activities is considered to begin with the pouring of concrete for the foundation of the plant (IAEA, 2019). The start of commercial operation is usually “declared” after several weeks to months of test operations have been completed and the plant begins operating full time. Because NPPs require a considerably longer amount of time to construct than competing technologies in the electricity sector, financing costs account for a comparatively greater proportion of capital costs for NPPs, around 17% under ideal conditions (Network, 2017; Rothwell, 2016) and even higher when delays stretch out construction schedules. The opportunity cost of capital during the construction period is commonly called “allowance for funds used during construction” in the electric utility sector.

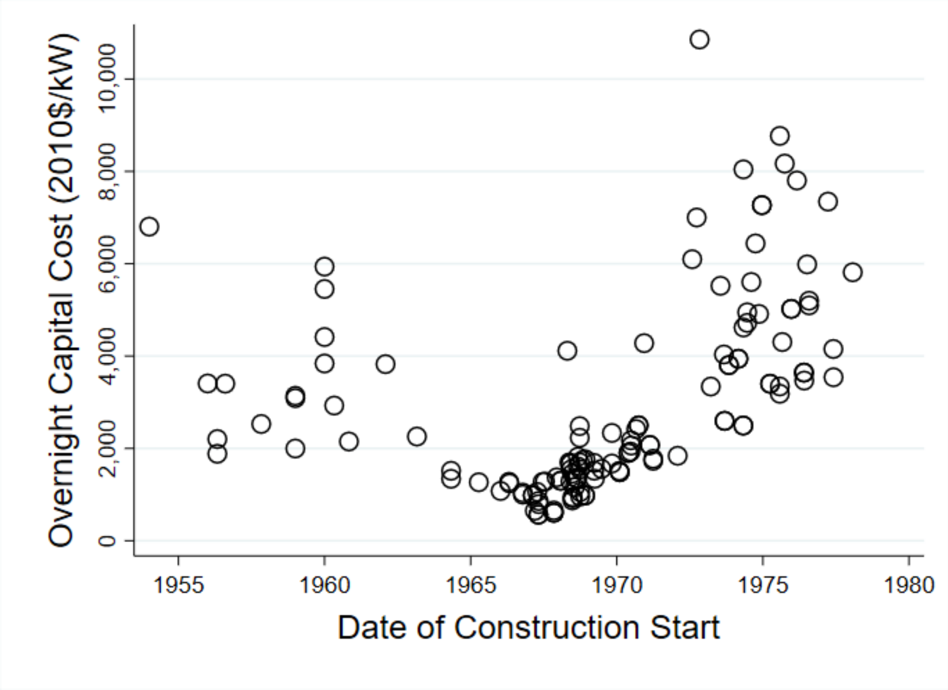

Figure 1.1: Overnight Capital Costs of NPPs in the United States

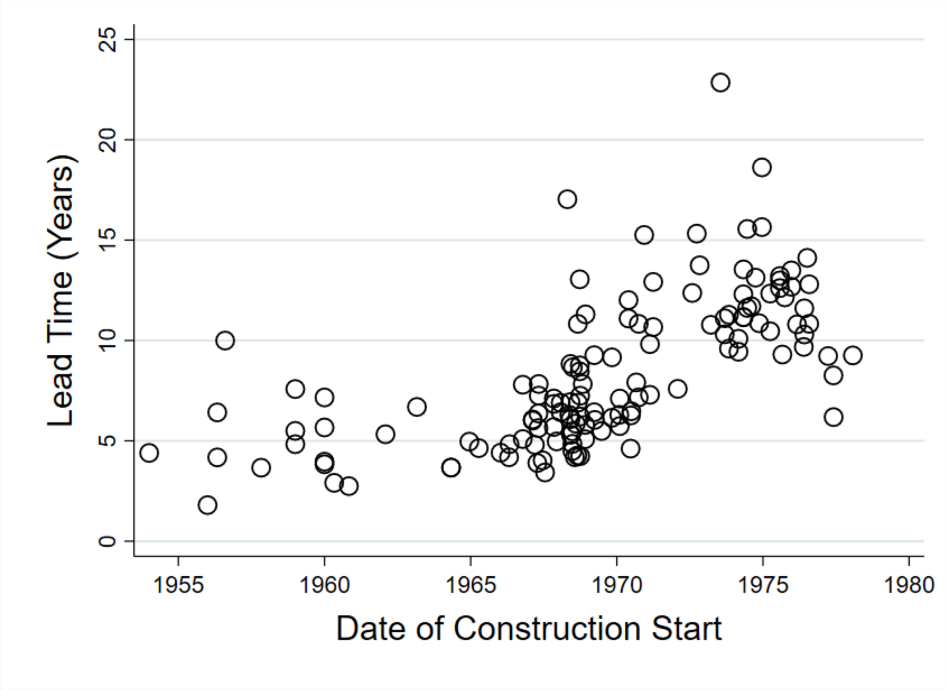

Figure 1.2: Lead Time of NPPs in the United States

1.1.2 Prior Quantitative Studies of OCC and LT

In this section, I will primarily review studies that estimate the effect of underlying casual determinants of OCC and LT for NPPs. But first I will briefly mention the prior works that collected and presented the necessary data on which subsequent analyses rely. These works have successively expanded data availability from the United States (Komanoff, 1981; Koomey and Hultman, 2007), to France (Grubler, 2010; Rangel and Lévêque, 2015), to several other OECD nations (Lovering et al., 2016), and finally 82%[1] of the global population of reactors (Portugal-Pereira et al., 2018). However, unlike the studies below and the present work, most of the foregoing works (with the exception of Rangel and Lévêque (2015)) do not analyze the underlying causal determinants of LT or OCC in a quantitative or systematic way.

Berthélemy and Escobar Rangel (2015) estimate a system of equations for OCC and LT in the United States and France. They conclude that the French policy of standardization helped reduce cost escalation and schedule slippage relative to the U.S. experience. Their estimated learning effects are conditional on experience from previous NPP construction being accumulated by the same architect-engineer (AE) firm with the same reactor model. Notably, the U.S. market for nuclear reactor design was contested by four major suppliers of nuclear reactors whose designs were routinely customized by approximately twenty different AE firms to meet the requirements of different utilities. In contrast, the French market was monopolized by Framatome as reactor supplier and monopsonized by the state-owned national utility, EDF, which performed in-house architect-engineering for its plants.

In addition, Berthélemy and Escobar Rangel estimate a model of LT alone on a larger sample, adding observations from Canada, the United Kingdom, Japan, and South Korea. This analysis lends further support for the hypothesis that standardization of reactor design

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[1] While Portugal-Pereira et al. (2018) limit their analysis to light water reactors, their data appendix provides OCC for 521 reactors.

helps to reduce lead time.

LT of the global population of NPPs was investigated by Csereklyei et al. (2016) using duration analysis.[2] The authors find several economic conditions influence NPP construction: higher levels of GDP per capita, higher expectations of future economic growth, and higher oil prices are associated with shorter lead times. Furthermore, they find partial evidence for the benefits of standardization. They show some—but not all—reactors of certain standardized designs tended to be built faster compared to those of non-standardized design.

Regarding political factors, Csereklyei et al. find both autocracy and democracy are associated with faster construction, where anocracy (Polity IV[3] score between -5 and +5) is the reference category. But the standard errors on the effects are very large; they find a statistically significant effect of democracy in only one econometric specification. They find no statistically significant effect of the accidents at Three Mile Island (TMI) or Chernobyl on lead time, which contrasts sharply with the conventional wisdom among industry observers, prior academic findings (Berthélemy and Escobar Rangel, 2015), and the results I find in Table 1.8 in Section 1.4.2.

In a series of three closely related papers (Sovacool et al., 2014a,b,c), Sovacool et al. analyze a sample of 401 projects in the electricity sector, consisting of several different types of power plants (fossil, nuclear, solar PV, solar thermal, wind, biomass) and high voltage transmission lines. They present data on budget overruns and schedule slippage (i.e. increased in OCC and lead time relative to original estimates). Comparing all the types of projects studied, they find that (1) NPPs most frequently exhibit budget overruns and (2) NPP budget overruns are, on average, the largest as a percentage of initial budget relative to all other technologies considered. Another noteworthy finding is that budget overrun and schedule slippage are

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[2] Duration analysis is also known as "survival analysis," so-called because it is classically used to estimate patient survival after a medical treatment. However, the method extends naturally to modeling the length of time between any two events.

[3] See Appendix A.3 for discussion on the Polity IV democracy-autocracy index.

positively correlated with each other for nuclear power plants.[4] This is consistent with the findings of Ref. Portugal-Pereira et al. (2018), who report a correlation of $r = 0.48$ between OCC and LT. United Engineers and Constructors (1986) (an American architect-engineer firm involved in several NPP projects) attribute the relationship between time and cost to the effect of delays on labor productivity. For example, failed inspections and design changes are said to have a "triple penalty"—the cost of the initial work, the cost of removing the initial work, and the cost of performing the work again. Such work comes also comes at the cost of a longer lead time.

For the present work, I have selected LT as the sole outcome of interest for several reasons. First, the data are available for the global population, which bolsters statistical power. Second, LT is a more transparent and consistently recorded metric, whereas OCC data are subject to disputes regarding accounting practices, inflation adjustment, currency conversion, and trustworthiness of data sources. Third, LT is an economically important outcome *per se*, as it plays an essential role in the accumulation of financing costs during construction and schedule slippage tends to correlate with budget overruns. Lastly, modeling the endogenous interactions between OCC and LT is beyond the scope of the present work. Future research could extend the present work by modeling the simultaneous determination of OCC and LT as in Berthélemy and Escobar Rangel (2015) while using the OCC data compiled by Portugal-Pereira et al. (2018).

1.1.3 Learning-By-Doing

Learning-by-doing is a theory of endogenous technological change that ascribes cost reductions and quality improvements to the accumulation of practical experience with a production process (Arrow, 1962). The conventional model of learning-by-doing posits the following re-

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[4] The authors report an R^2 of 0.316 in regression of schedule slippage on budget overrun, using a polynomial fit. The estimated fit is nearly linear, so the implied coefficient of correlation is approximately 0.56.

lationship between some outcome Y_t (typically, cost per unit) and cumulative experience, Exp_t, based on the work of Wright (1936):

$$ln(Y_t) = \alpha + \beta ln(Exp_t) + \epsilon \tag{1.1}$$

Assuming lower values of the outcome are more desirable, the production process is said to exhibit learning-by-doing when $\beta < 0$. In practice, as a technology matures, the level of the outcome over time ceases to be characterized by Equation 1.1 and reaches some relatively stable level. This level would be determined exogenously by physical limits to the production process and the price of inputs.

A common method for contextualizing the magnitude of β is the progress ratio (PR) or learning rate (LR):

$$1 - 2^{\beta} = 1 - PR = LR \tag{1.2}$$

PR is interpreted as the relative level of the cost (or other outcome) after a doubling of cumulative production as compared with the prior level; LR is the percentage reduction in cost (or other outcome) arising from a doubling of cumulative production. For example, $\beta = -.32$ generates $PR = 80\%$ (a cost equal to 80% of the prior level) and $LR = 20\%$ (a 20% reduction in cost).

Several improvements to the operating performance of nuclear power plants have been documented, such as increased reliability (Joskow and Rozanski, 1979a; Davis and Wolfram, 2012), increased power output (Davis and Wolfram, 2012; NRC, 2012), reduced occupational exposures to radiation (Brock et al., 2020), and reduced rates of initiating events (precursors of more serious safety problems) (Johnson and Schroeder, 2017). However, the empirical evidence regarding learning in NPP construction paints a more dismal picture. Rubin et al. (2015) survey the literature on learning-by-doing in the capital costs of energy technologies, reporting mean one-factor[5] learning rates of 15% for natural gas combustion

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[5] The foregoing discussion has been solely of one-factor (cumulative experience) learning. Two-factor

turbines, 12% for wind turbines, 23% for solar photovoltaic (PV), and 11% for biomass generation, *inter alia*. Their review of learning rates for nuclear power captures only four studies, which report values ranging between -38% (Grubler, 2010) and 5.8% (Kouvaritakis et al., 2000). Subsequent to the public release of more authoritative data on the costs of France's nuclear reactor fleet, Rangel and Lévêque (2015) argued that the cost estimates underlying the calculations of Grubler (2010) were too high for later reactors. The findings of Berthélemy and Escobar Rangel (2015) correspond to a learning rate of 10%,[6] conditional on the same design of plant being built by the same architect-engineer.

One hypothesis for the poor rate of learning in NPP construction is the high degree of on-site construction work as a share of the total cost. Estimates from United Engineers and Constructors (1986) suggest that equipment manufactured off-site accounts for approximately 21% of the base cost[7] of a typical American pressurized water reactor built in the 1980s. Factory fabrication is theorized to better facilitate learning-by-doing (Bertram et al., 2019), for reasons such as assembly line production methods, a stable workforce, and consistent and well-controlled workplace conditions. Lessons learned at one construction site may not disseminate as readily to the next site, such as when different workers are employed at the two sites.

A strong contrast can be drawn between nuclear fission and solar PV in this respect. The price of PV modules constituted 74% of the total cost of rooftop solar panel installations in Germany in 2007; following dramatic declines in global module prices, that share fell to 39% as of 2019 (Philipps and Warmuth, 2020). This decline is consistent with evidence for faster learning in PV module manufacturing than in PV module installation. Elshurafa et al. (2018) estimate a learning rate of 11% for balance-of-system costs of solar PV installations, whereas

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learning encompasses cumulative experience and the stock of knowledge. See Wiesenthal et al. (2012) for further discussion.

[6] $1 - 2^{-.152} = 10\%$

[7] Author's own calculations from Table 5-3 of United Engineers and Constructors (1986). "Base cost" includes all costs in overnight cost except for the contingency allowance (Rothwell, 2016, p. 78), the amount budgeted to cover unexpected expenses.

the median learning rate for PV modules among the studies included in Rubin et al. (2015) is 20%.[8] Furthermore, the high initial share of cost associated with the module provided a greater scope for manufacturing-based learning effects to reduce the overall capital cost of solar PV.

Many commentators emphasize the role of standardization in fostering beneficial learning effects in the nuclear industry (Ingersoll, 2009; Rangel and Lévêque, 2015; Berthélemy and Escobar Rangel, 2015; Lovering et al., 2016). However, technologies such as solar panels, wind turbines, and gas combustion turbines appear to have achieved considerable learning despite a much larger number of firms engaged in each industry, with each firm offering competing designs, relying on proprietary innovations, and regularly introducing new product lines. Why is cumulative industry experience a meaningful predictor of cost reductions for these technologies but not for nuclear power?

To illustrate this, consider the example of General Electric (GE), a large multinational firm engaged in a variety of industries, including several different energy technologies. GE currently advertises 21 different models of gas combustion turbine on its website (General Electric, n.d.), many of which come in two different versions depending whether the customer's grid runs at 50 Hz or 60 Hz. This high diversity of product offerings—and the development costs that each product entails—is sustained by a large volume of orders. GE boasts that over 1,100 of its F-class turbines have been installed at power plants to date (General Electric, No date.), the first of which entered commercial operation in 1990 (Patel, 2019). GE claims sales of over 3,000 units of its smaller B and E class turbines. Such a high volume of sales can sustain serial manufacture of several different, standardized models.

Now consider GE's involvement in the nuclear industry. GE was the first commercialize boiling water reactor (BWR) technology, beginning with Dresden Unit 1 in 1960. To date, a mere 99 commercial-scale BWRs have been built by GE and firms to which it licensed

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[8] Author's own calculations from Table A3 of Rubin et al. (2015).

its technology. These 99 reactors consist of several different product lines and most of these exhibit a staggering degree of internal diversity (Gavrilas et al., 1995). BWR-1 is a designation retroactively applied to a hodgepodge of early designs, which is perhaps to be expected in the early stages of technological development. The BWR-2 was obsolete before the first one had entered commercial operation[9], as GE quickly returned to the drawing board and the first BWR-3 began construction several years earlier.[10] BWR-4s and BWR-5s have been mixed and matched with the Mark I and Mark II containment designs.[11] The BWR-6 started to exhibit more standardization; it was exclusively paired with Mark III containment and GE applied to the US Nuclear Regulatory Commission for approval of a "Standard Safety Analysis Report." Yet the BWR-6 was offered in three different sizes of reactor pressure vessel, each requiring its own safety analysis. The first truly standardized BWR was the ABWR, of which four have been completed to date.[12] While the scale of the GE BWR installed base is impressive in terms of megawatts (roughly 82.5 GW), the scope for learning through repetition of a standardized design has been historically quite narrow.

Of course, learning-by-doing is not limited to improvements in the ability of workers and firms to perform an production process more efficiently. It also encompasses improvements in the design of the product. For example, a reduction in the number of external recirculation loops from five to two was a major breakthrough in the design of the BWR-3 and a reason for the quick discontinuation of the BWR-2. David and Rothwell (1996) consider the question of how firms balance between the competing considerations of standardization and experimentation through diversity. On one extreme, consider repeated construction of identical plants, which permits learning only to occur in the efficiency of the manufacturing and construction process. On the other extreme, imagine iterated construction of one-of-a-kind plants. Such diversity provides fertile ground for experimentation and allows for the possibility of improvements to

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[9] Oyster Creek, Dec. 1, 1969

[10] Dresden Unit 2, Jan. 10, 1966

[11] Seven BWR-5s were built with Mark I containment in Japan by Toshiba and Hitachi, licensees of GE technology.

[12] Two ABWRs began construction in Taiwan but were never permitted to operate due to political decisions.

the design of future plants. However, it comes at the cost of workers and managers constantly readjusting to a new production process, as well as fixed development costs for each new design. Of course, between these two extremes exists a continuum of possibilities. The appropriate balance between experimentation and standardization is a problem of dynamic optimization under considerable uncertainty.

1.1.4 Megaproject Syndrome

An alternative hypothesis regarding learning in NPP design and construction is the view learning did indeed occur, but the cost-reducing and time-saving effects of learning were swamped by countervailing factors. Prime suspects for countervailing factors include upward ratcheting of safety requirements (Paik and Schriver, 1980), regulatory delays in the granting of operating licenses (Rothwell, 2016), and diseconomies of scale (Adams, 1996; Ingersoll, 2009). One theoretical explanation for diseconomies of scale concerns the dispersal of decay heat after a reactor is shutdown. "...[C]ore power (and decay power) is proportional to the volume of the core, which varies as the cube of the effective core radius. On the other hand, heat removal from the vessel is proportional to the vessel surface area, which varies roughly as the square of the core radius."(Ingersoll, 2009) Thus, as reactors grew in size, ever more powerful and elaborate systems were needed to ensure control of decay heat under emergency conditions.

However, if diseconomies of scale are present in nuclear reactors beyond a certain size, then it is puzzling why some firms in the industry continue to pursue even larger designs, such as the EPR (1,650 MW) and the APR-1400 (1,340 MW). Surely identifying optimal scale is part of the learning process. The promotion of SMRs and the proliferation of venture-capital-backed firms pursuing SMR development implies a lack of consensus within the industry regarding what lessons should be learned from the scale-up of NPPs in the 20th century.

A large academic literature on so-called "megaproject syndrome" theorizes that persistent economic problems in the construction of large-scale infrastructure is not merely a failure of technical optimization (Flyvbjerg et al., 2003; Van Marrewijk et al., 2008; Merrow, 2011; Flyvbjerg, 2014). Nuclear power plants are but one category of megaprojects; examples of others include dams, airports, bridges, tunnels, harbors, public transit, and high-speed rail. Uniting characteristics of megaprojects include: a budget above $1 billion (although some authors argue for lower thresholds in certain sectors or in the context of less developed nations); customization as necessitated by unique geographic conditions or customer requirements; extensive involvement of the public sector in matters such as planning, permitting, and financing; complex management challenges arising from a large number of subcontractors.

Several theories have been considered in the literature regarding the high propensity of megaprojects to run over budget, fall behind schedule, be abandoned prior to completion, and fail to deliver the level of benefits promised once in operation. The classical view is that the incentive structure faced by politicians and project managers produce optimistically biased and/or strategically underestimated estimates of cost and schedule (Flyvbjerg et al., 2002). Alternative views emphasize, *inter alia*, scope change (Greiman, 2013), corruption (Locatelli et al., 2017), cross-purposes and infighting among project partners (Lenfle and Loch, 2017), and relations with external stakeholders (i.e. parties other than the project owner and the firms delivering the project) (Olander and Landin, 2008). I take the view that all of these theories are in no way mutually exclusive; in some cases, they could be mutually reinforcing. However, in this chapter, I focus on the role of external stakeholders—the local community, civil society organizations dedicated to the environment or advocacy for utility ratepayers, and enterprising politicians—in contributing to megaproject syndrome. I theorize that a higher degree of political decentralization enables external stakeholders to more substantively impact the design, permitting, and construction of megaprojects such as nuclear power plants.

1.1.5 Decentralization

Decentralization has been in vogue as a development strategy promoted by major international institutions (e.g. the World Bank and International Monetary Fund) since the closing decades of the 20th century; the recommendation has been increasingly accepted by a variety of countries (Bardhan, 2002; Faguet and Pöschl, 2015; Martinez-Vazquez et al., 2017). The advice is motivated by a large and well-established literature that spans political economy, economic history, and development. Purported benefits of decentralization include greater public sector efficiency (Adam et al., 2014), greater accountability (Agrawal, 1999), lower corruption (Lessmann and Markwardt, 2010), opportunities for yardstick competition (Besley and Case, 1995), and self-enforcing government commitment to markets (Weingast, 1995).

At first glance, there may be limited applicability of the lessons from this literature to the case of nuclear power. Historically, national governments have assumed sole authority for the regulation of safety at NPPs, with the notable exception of West Germany (and reunited Germany post-1990), where authority is shared between the *länder* and the federal government. National control of nuclear safety regulation limits the scope of subnational regulation of the industry to policy areas such as land use, environmental permitting, and rate-setting for regulated electric utilities. These are important aspects of the regulatory environment faced by firms in the nuclear industry, and they have a long history as the setting for political conflict over nuclear power (Joppke, 1992), as will be discussed further in Section 1.1.6.

The consequences of what might be considered “inefficient regulation”—such as delaying or cancelling the construction of nuclear power plants and discouraging investment in the nuclear supply chain—are often intentional. The literature on decentralization primarily studies outcomes that are valence issues for voters—that is, issues on which all voters agree on the desired outcome, even if they may disagree on the optimal policy to achieve that outcome. Examples of valence issues include economic growth (faster is better), crime rates (lower is better), and corruption (lower is better). How does decentralization operate when the issue in question is a controversial technology over which opinions differ?

1.1.6 Local and Regional Opposition to Nuclear Power Plant Siting

The politics of nuclear power has historically featured opposition by citizens, civil society, and politicians who are geographically near the site of proposed and existing NPPs. This has been documented in the United States (Joppke, 1992; Wellock, 1998; Berndt and Aldrich, 2016), France (Aldrich, 2010), West Germany (Surrey and Huggett, 1976), the United Kingdom (Welsh, 1993), several separatist regions in Western Europe (Kurlansky, 1981), Japan (Aldrich, 2010), and even the Soviet Union in its final years (Dawson, 1995). Such opposition is often characterized by the acronym NIMBY ("not in my backyard")(Aldrich, 2010; Welsh, 1993). Some scholars view the term as inherently pejorative, conveying a normative disapproval of opponents' position and motivations (Burningham, 2000). To avoid the appearance of passing an unnecessary normative judgement within the context of a positive analysis, hereafter I characterize the phenomenon as local and regional opposition to NPP siting, or "local opposition" for brevity.

The success of local opposition to NPPs has varied widely across nations, regions, and communities. A first-order explanation is to attribute siting outcomes to the magnitude and persistence of mobilization campaigns. In *Site Fights*, Aldrich (2010) provides a comparative history of local opposition to NPP siting in Japan and France. Meaningful contestation of pro-nuclear policy in the national halls of power was almost entirely absent in both countries in the late twentieth century. Furthermore, both Japan and France are unitary nations, meaning all sovereignty is vested in the national government. Thus, the ability of local and regional governments to conduct policy at cross-purposes with the central government is necessarily circumscribed.

However, France and Japan contrast sharply with respect to actions taken by their central governments to ameliorate or overcome local opposition. Initiatives by the Japanese central government tended toward “soft social control”: propaganda, public meetings, offering tours of other nuclear power plants, and—most especially—generous transfer payments *à la* Coase to municipalities, fishermen, and farmers. France, by contrast, engaged in the methods of “hard social control,” such as police presence (and police violence), expropriation of land, surveillance, secrecy, restrictions on public participation, and simply ignoring local opinion. Aldrich argues that the difference in approaches resulted from the persistence of opposition in Japan and the withering away of opposition in France. In the face of persistent opposition, the state is obliged to “win hearts and minds.” Conversely, if opposition demobilizes after a proverbial “whiff of grapeshot,” the state sees no need to take another approach. Comparing the results of the French and Japanese nuclear programs, Aldrich writes:

> *Analysts point out that without only a few exceptions, “the government [of France] implemented its initial plans” for siting reactors (Rucht 1994, 153), an accomplishment far surpassing Japan’s record, where close to half the sitings failed.*

While Japanese utilities regularly withdrew proposals in response to local opposition, it seems likely that they benefited considerably from only moving forward with construction in communities that had agreed to host NPPs. Once regulatory approval is granted and construction begins, the lead time for constructing and commissioning an NPP in Japan has historically been extraordinarily fast and stable, averaging 4.7 years[13] and showing modest declines from the 1970s to the 1990s. By comparison, the global average lead time is 7.4 years. Construction in France was once faster than the global average, as well, averaging

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[13] Author’s own calculations from IAEA PRIS. This average is for plants which have been completed as of the time of writing. Thus, two reactors that remain under construction are excluded.

6.2 years for plants starting construction prior to 1980. That figure has trended upwards, averaging 9.0 years for the plants beginning construction in 1980 or later, and it is certain to rise further with the eventual completion of Flamanville 3.

Circumstances in Japan and France contrast sharply with those in United States, where local opposition has historically been neither placated nor denied political and legal avenues by which to obstruct NPP construction. Cohen, McCubbins and Rosenbluth (1995) argue that a multiplicity of veto points in the constitutional design of the United States laid the groundwork for vigorous contestation of nuclear policy, including at the state and local level. Emphasizing the federal nature of the United States, Joppke (1992) points to three specific issues for which local opposition played an important role in delaying and cancelling NPP construction:

> *The three predominant issues of the U.S. nuclear power controversy in the 1980s—emergency planning, utility rate regulation, and waste disposal—are all similar in this regard. In each case, local citizen groups formed effective alliances with local and state authorities in opposition to particular nuclear facilities or federal regulatory agencies.*

Critical Masses: Opposition to Nuclear Power in California, 1958-1978, by Wellock (1998), is instructive of the causal mechanisms by which political decentralization would tend toward lengthening NPP lead times globally. For example, Diablo Canyon Power Plant in California was the target of public protests throughout its construction period, drawing record-breaking crowds, celebrities, and Governor Jerry Brown. Seismic safety was among activists' leading concerns about the plant. State bureaucracies such as the Natural Resources Agency, the State Lands Commission, the Public Utilities Commission offered ample opportunities for local opposition groups to intervene in the process, demand transparency from the utility, and force it to adjust its behavior. While construction of Diablo Canyon had begun in 1968 and was effectively complete in 1973, it was not permitted to enter commercial operation until 1985 after major seismic retrofits. While formally licensing decisions were in the hands of the federal bureaucracy, Wellock presents a strong case for the role of state government and local activists in pushing for stricter regulatory scrutiny.

A principal theme of *Critical Masses* is the emergence of a post-materialist environmentalist ethos. This ethos places little weight on economic concerns, distrusts technocrats and technocratic institutions, and emphasizes values such as local control, preserving the aesthetic character of natural vistas, and opposition to war. Berndt and Aldrich (2016) report empirical evidence from the United States that proposed and under construction NPPs were more likely to be abandoned in counties with higher incomes, which they consider to be a proxy measure of post-materialist values. On the other hand, Berndt and Aldrich find no relationship between local political affiliation and siting outcomes. They conjecture that ideological stances on environmental issues had not yet been mapped onto polarized partisan identities as they are in the present day.

Several authors have commented on the importance of a coherent, stable, long-term policy commitment to the nuclear industry in enabling its success. Delmas and Heiman (2001) argue that fragmentation of power prevented the United States from making such a commitment. In case studies of China, India, South Korea, and Japan, Sovacool and Valentine (Sovacool and Valentine, 2010a,b) conclude that "centralization of national energy policymaking and planning" is one of six key factors for successful NPP deployments. They note, for example, that "in South Korea, the Office of Atomic Energy was placed directly under the President and the nuclear program was structured as a monopoly under the Korea Electric Power Corporation." However, even South Korea—arguably the world leader in centralization, standardization, and successful learning-by-doing in the nuclear industry (Lovering et al., 2016)—offers a lesson in how decentralization can impede timely NPP construction:

> *Yonggwang*[14] *was one of the first of the state-owned utility (Korea Electric Power Co — KEPCO) projects to attract serious local opposition. Political reform in South Korea has devolved some power from the centre. Local politicians in Yonggwang used their new strength to slow down construction.*
>
> *Hanjung (Korea Heavy Industries and Construction) was due to begin construction in December 1995, but a delay was brought on by the cancellation of construction permits for the site by Yonggwang County, South Cholla Province.* (Power Technology, n.d.)

1.1.7 The Logic of Local Democratic Control

In this section, I draw on the framework of Mançur Olson's seminal work, *The Logic of Collective Action* (Olson, 1965), to argue that the spatial distribution of costs and benefits from nuclear power plants tends to generate a pattern of support by national governments and opposition by local and regional governments. The reasoning herein follows along the same lines as those in the introductory chapter of *Site Fights* (Aldrich, 2010).

The standard problem considered by Olson posits some policy provides concentrated benefits to a small group and diffuse costs to the rest of society. Lobbying the government to advocate for or against the policy requires overcoming a collective action problem, as no one individual can meaningfully influence the outcome. Olson argues that this situation inherently favors small groups for two reasons. First, the costs of overcoming collective action problems (such building sufficient solidarity to overcome free-riding incentives and coordinating on a common strategy) are increasing in group size. Second, the benefits of a policy change can be quite large on a per-person basis for the sorts of small groups and policies typically considered.

To analyze the political economy of nuclear power plant construction, I modify Olson's prob-

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[14] Yonggwang NPP was renamed Hanbit NPP in 2013.

lem in three ways. First, I give a spatial dimension to group identity and interest: proximity to a proposed nuclear power plant. Those who live within the range of a hypothetical evacuation or exclusion zone in the event of a catastrophic nuclear accident are the small group; those who live further away and yet would still benefit from the plant in some way are the rest of society.

Next, I invert the distribution of costs and benefits. The small group faces a geographically concentrated risk while the rest of society stands to gain geographically diffuse benefits. Of course, there is also a geographically concentrated benefit in the form of increased local economic activity. However, it is not unheard of for residents to regard this benefit as a cost. Local opponents of a proposed nuclear power plant near Bodega Bay, California argued that a large industrial facility would ruin the rustic charm of their small fishing community by attracting further development (Wellock, 1998, pp. 25-28).

The primary diffuse benefit of interest is the electricity produced by the plant, which can be transmitted by the electricity grid to households and firms hundreds of miles away. The electricity may not be particularly valuable if substitute sources of electricity can be had at little, zero, or negative additional cost. However, other diffuse benefits include clean air and water,[15] lessening of national dependence on expensive energy imports,[16] complementarities with national nuclear weapons development,[17] and interregional technological spillovers arising from learning-by-doing.

In a final modification of Olson's original framework, I observe that democratic subnational government is a ready-made solution to the collective action problem faced by local residents who oppose a nearby nuclear power plant. Elected politicians are strongly incentivized to

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[15] Assuming the substitute sources of electricity are polluting. Historically, this has been the case (Kharecha and Hansen, 2013).

[16] Even for nations which depend on uranium imports, importing uranium is much cheaper per unit of final electricity generated than fossil fuels. Provided the nation is a signatory to the Non-Proliferation Treaty, availability of supply is a non-issue.

[17] Of course, nuclear weapons programs generate negative externalities globally but plutonium recovered from spent nuclear fuel is often considered a benefit by national policymakers who desire nuclear weapons.

care about the interests of constituents in their jurisdiction and may take on the cause of opposing NPP construction as an electoral strategy. Even when the issue does not immediately arouse the attention of subnational politicians or those politicians favor the plant, the subnational government offers a more convenient forum with lower transaction costs in which local opponents of a nearby NPP can mobilize and seek to effectuate policy. A subnational government with sufficient autonomy and institutional capacity can directly intervene to regulate NPP construction on issues such as land use, environmental protection, or economic regulation of utilities without ever needing to lobby or influence the national government.

Of course, the reasoning here can be applied to a variety of political economy problems of a spatial nature, such as residential zoning, routing of high-speed rail lines, or the provision of services to the mentally ill and homeless. In the case of nuclear power, I propose it may explain partially patterns we see in the data on NPP lead times.

1.2 Data

I assembled a database of all commercial nuclear power reactors which have ever initiated construction, as of April 6^{th}, 2021. The observations are identified by the Power Reactor Information System (PRIS) of the International Atomic Energy Agency (IAEA). While certain basic information about each NPP is available on the IAEA's public website and through their various publications, I was granted temporary access to a private version of the PRIS database restricted to authorized users. The dataset I have assembled offers considerably more detail and comprehensiveness than any other prior work on this topic, to my knowledge. Past studies are typically limited to variables such as size of the reactor in megawatts, general type of reactor (PWR, BWR, etc.), the identity of the firm responsible for the design of the nuclear steam supply system (NSSS), and a coarse coding of reactor models (e.g., Csereklyei et al., 2016). The most fine-grained coding of reactor models can be found in the data appendix to Portugal-Pereira et al. (2018). However, it suffers from the same inconsistencies present in the raw IAEA PRIS data. For example, American BWRs are coded as a concatenation of the design of NSSS (BWR-1, BWR-2, etc.) and the design of the containment structure (Mark I, Mark II, Mark III), whereas BWRs in other countries are purely coded by their design of NSSS. Similar inconsistencies abound for other types of reactors.

Unfortunately, the terms and conditions of my access to PRIS prohibit me from sharing any of its data that are not otherwise publicly available. This primarily limits the sharing of data on the technical specifications of reactors. Those data available for public dissemination can be found at `https://github.com/a-g-benson/Global-NPP-Database`. Below, I will briefly describe the key variables central to the analysis and present certain summary statistics. A complete description of the data sources, cleaning, and variables can be found in Appendix A.

Table 1.1 tabulates the observations by country and geopolitical region. Countries were assigned to regions based on a constellation of factors, primarily their alliances, form of government, and economic system during the Cold War. Detailed discussion of the coding scheme is reserved to Appendix A.3.

1.2.1 Lead Time

Lead time is computed as the time between the date on which construction began—the first day on which concrete for the foundation was poured—and the date of commercial operation, less any time during which construction was totally suspended.

The mean lead time in the dataset is 7.4 years, with a standard deviation of 3.3 years. There are clear geographic patterns to the data, as summarized in Table 1.2 and plotted in Figure

1.3. Notably, East Asian nations construct NPPs significantly more quickly and consistently, with a mean 5.5 years and a standard deviation of 1.4 years. The mean lead time in Western nations does not differ substantially from the global mean, which is perhaps unsurprising given that NPPs in Western nations account for 55% of the sample.

1.2.2 Reactor Typology

PRIS uses the term "type" to encapsulate broad similarities in the principles of a reactor's design. The most common types are pressurized water reactors (PWR), boiling water reactors (BWR), pressurized heavy water reactors (PHWR), gas-cooled reactors (GCR), and light water graphite reactors (LWGR). I aggregated all other types were into a single category called "other" due to a sparsity of observations.

Summary statistics by type of reactor are presented in Table 1.3. Light water graphite reactors (LWGRs), which were exclusively built in the Soviet Union, exhibit the quickest average lead time, as well as the lowest standard deviation. In a close second place are boiling water reactors, which are largely found in the Western Bloc and Japan. Pressur-

Western Bloc		**Eastern Bloc**		**East Asia**		**Other**	
U.S.A.	133	U.S.S.R.	69	Japan	59	India	22
France	70	Czechoslovakia	13	China	49	Pakistan	5
United Kingdom	45	Russia (post-1991)	8	South Korea	26	Argentina	3
West Germany	30	East Germany	6	Taiwan	6	Mexico	2
Canada	25	Bulgaria	6			Brazil	2
Sweden	13	Hungary	4			South Africa	2
Spain	10	Romania	2			Yugoslavia	1
Belgium	8					Iran	1
Switzerland	6					U.A.E.	1
Italy	4						
Finland	4						
Netherlands	2						
Subtotal	**350**	**Subtotal**	**108**	**Subtotal**	**140**	**Subtotal**	**39**

Table 1.1: Count of Completed Reactors by Country, as April 6, 2021.

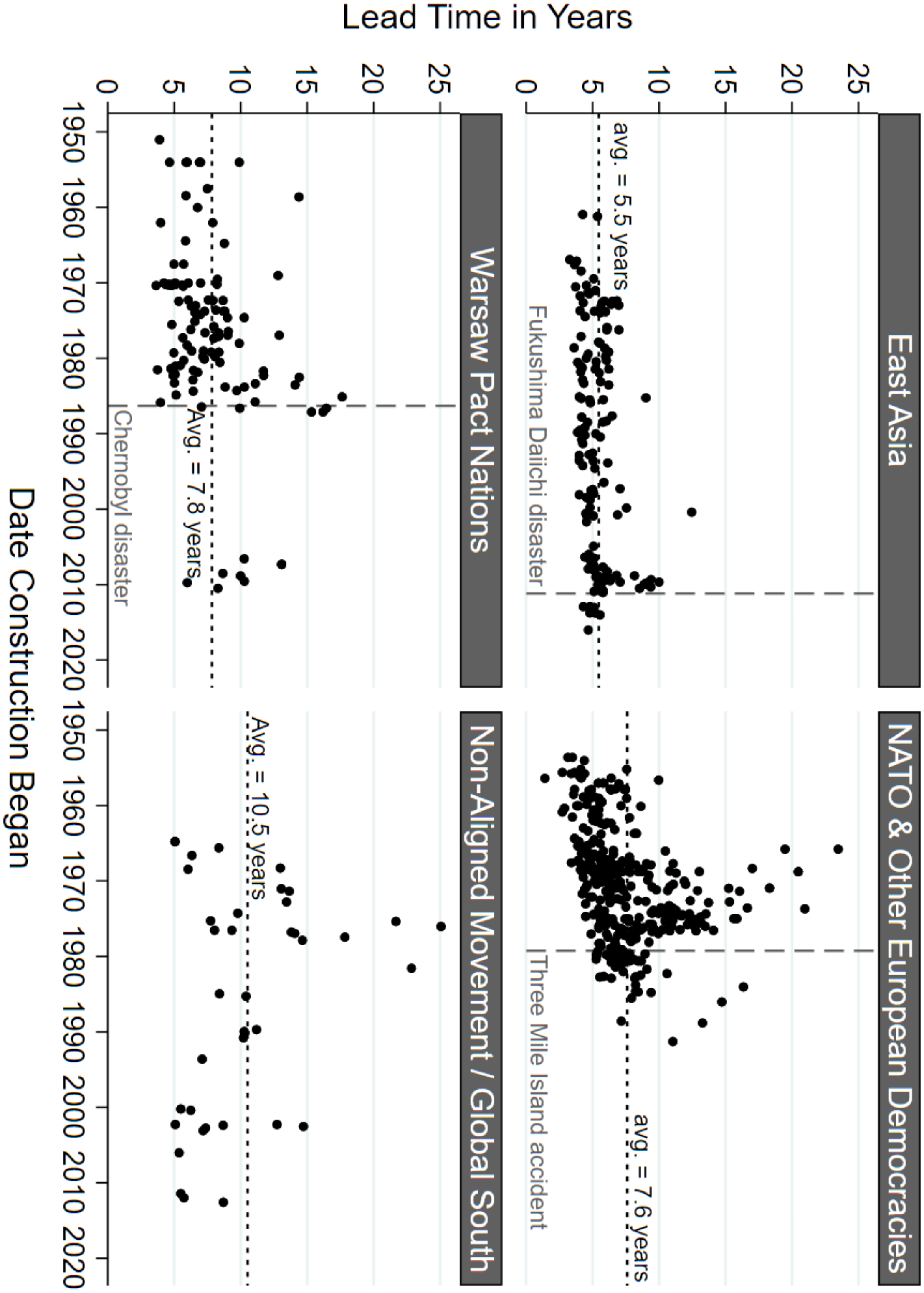

Figure 1.3: Divergent Regional Trends in NPP Lead Time

Region	**Mean**	**Std. Dev.**	**N**
Western Bloc	7.6	3.4	350
Eastern Bloc	7.7	2.9	106
East Asia	5.5	1.4	139
Global South	10.6	5.0	38
World	**7.4**	**3.3**	**633**

Table 1.2: Descriptive statistics of NPP lead time (in years) by region.

Acronym	**Reactor Type**	**Mean**	**Std. Dev.**	**N**
PWR	Pressurized Water Reactor	7.5	3.2	359
BWR	Boiling Water Reactor	6.5	3.0	116
PHWR	Pressurized Heavy Water Reactor	8.3	3.4	57
GCR	Gas-Cooled Reactor	7.6	4.9	52
LWGR	Light Water Graphite Reactor	6.5	1.5	30
Other	miscellaneous reactor types	8.3	3.4	23
Total		**7.4**	**3.3**	**637**

Table 1.3: Lead time (in years) by type of reactor.

ized water reactors (PWR) are exactly at the global average, which is unsurprising given that they account for 56.3% of the global population. Pressurized heavy water reactors (PHWRs) perform relatively poorly, although this average is heavily influenced by three countries: Argentina and Romania (which suspended construction on theirs for many years due to economic and political conditions) and India (whose nuclear power program developed with little international support as a consequence of the international response to India's acquisition of nuclear weapons). Excluding these three countries—which account for roughly 40% of PHWR observations—the lead time of the remaining PHWRs is 6.7 years.

I use the term "family" to classify reactors which share an evolutionary heritage. This classification is narrower than reactor type in that a family encompasses only reactors by a single firm or a small set of firms which have a history of licensing intellectual property and collaborating with one another. The classification scheme is detailed in Appendix A.2.

The most granular typology of reactor is the model. Where applicable, I use the model names assigned by the manufacturer, such as AP-1000, CP1, P4, OPR-1000, CNP-300, VVER-213, and ABWR. For standardized reactor designs, this identification comes as close as realistically possible to identifying "identical" reactors. However, for non-standardized designs, PRIS provides an abbreviated, generalized description of the reactor's design in place of a model name. For example, "WH 4LP (DRYAMB)" indicates that the reactor is a Westinghouse design with four primary coolant loops and the containment structure operates at ambient atmospheric pressure. Information about the containment design was divorced from the name of the reactor model and used to populate a separate categorical variable relating to containment.

1.2.3 National Political and Economic Characteristics

Decentralization is my independent variable of interest. As my primary measure, I adopt the "self-rule" sub-index from the Regional Authority Index (RAI) by Hooghe, Marks, Schakel, Niedzwiecki, Osterkatz and Shair-Rosenfield (2016). They evaluate the constitutions and political histories of individual countries and they systematically scored them on matters such as the role of subnational governments in approving constitutional change, whether the central government holds a veto over subnational decisions, and the autonomy of subnational jurisdictions in setting their tax base and rates. For robustness, I also test my hypotheses against a binary indicator of whether a country has a federalist or unitary constitution. Table 1.4 reports the descriptive statistics for decentralization for both measures.

Region	**Has Federal Constitution**		**RAI Self-Rule Index**	
	mean	n	mean	n
East Asia	0.00	140	11.3	140
Western Bloc	0.58	350	17.0	350
Eastern Bloc	0.83	108	11.6	8
Global South	0.92	39	17.7	36
World	**0.51**	**637**	**15.5**	**534**

Table 1.4: Descriptive Statistics of Decentralization by Global Region

A t-test of the difference in mean lead time between federalist and unitary countries rejects the null hypothesis of no difference, finding federalist nations take 18 months longer on average ($t = -2.12$)[18]. Lead time correlates with the continuous measure of decentralization at $r = 0.167$.

Because decentralization may correlate with other important country characteristics, I also include measures of GDP per capita, democracy, and regime change. I rely on the historical estimates of GDP per capita from the Maddison Project (Bolt et al., 2018). For democracy, I use the "Polyarchy" index of electoral democracy generated from the Varieties of Democracy (V-Dem) Project (Coppedge et al., 2019). To identify the dates and magnitudes of changes of a country's constitutional structure or regime type, I rely on data from Polity IV (Marshall et al., 2018). I assign a value of 1 to a reactor if it was under construction (or in a period of temporarily suspended construction) during an episode of major regime change, and zero otherwise.

1.3 Econometric Specifications

Appendix B discusses an assortment of econometric issues that are common to many or all of the specifications which follow. Here, I summarize its conclusions briefly. In Section B.1, I argue that political institutions (democracy, decentralization, and regime change) are exogenous to nuclear power plant construction. In Section B.2, I account for a special type of measurement error that arises from serial construction. In Section B.3, I investigate possible selection bias arising from abandoned construction and conclude that it is negligible. In Section B.4, I explain how I control for the effect of major nuclear accidents and political events on lead time using an instrumental variables strategy. In Section B.5, I define cumulative experience as the count of reactors of the same family as reactor i that began construction

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[18] The bootstrap procedure was employed to calculate a standard error clustered by country.

prior to reactor i. Table B.4 lists all symbols used in the equations for this section.

For lack of quantitative measures of cross-nationally comparable, site-specific local opposition, the hypotheses tested in this paper assume the presence of local opposition. Given the literature I reviewed in 1.1.6 documenting the presence of local opposition in both unitary and federalist nations, I argue that this is a reasonable, albeit imperfect, assumption. My analysis focuses on identifying the channels through which political decentralization operates. While the credibility of the analysis *qua* causal inference is limited, the results can help guide future research by narrowing the range of likely explanations for raw correlation between decentralization and NPP lead time.

1.3.1 Modeling Mechanism 1: Politically Constrained Design

While summary statistics show that NPP lead times tend to be longer in federalist nations than in unitary nations, we must ask whether they build comparable nuclear power plants. Federalist and unitary nations may systematically choose different designs of reactors that have differing technical, safety, and economic characteristics. Do lead times differ because of these differences in design, or is it because of factors beyond the design of the plant? To test this hypothesis, I conduct the analysis in two steps.

First, I investigate which design characteristics have meaningful impacts on lead time in a regression with country fixed effects. The country fixed effects are intended to generate credible estimates of the average treatment effects of design characteristics on lead time by leveraging only within-country variation in design characteristics. The econometric specification is as follows:

$$ln(LT_i) = \sum_{s \in S} \theta_s Spec_{s,i} + \delta_r + \gamma M_i + \mu_c + \nu_t + \varepsilon_i \tag{1.3}$$

The selection of $Spec_{s,i}$ variables was guided by 5-fold cross-validation.[19] An additional con-

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[19] See Arlot et al. (2010) for an introduction to the method

sideration was sample size; including design characteristics for which too many observations have missing values would limit the sample size of the subsequent analyses. Refer to Table 1.5 for the list of variables ultimately included. δ_r represent fixed effects by type of reactor (e.g. BWR, PWR).

The year fixed effects ν_t control for any number of time-related variables which might otherwise be spuriously correlated with the regressors. For example, gas-cooled, graphite-moderated reactors have fallen out of favor in the two countries that have historically built them in meaningful numbers, the United Kingdom and France. Without year fixed effects, the estimated coefficient for this type of reactor—which both nations eventually judged to be technically and economically inferior to PWRs—could be biased downwards due to most of these reactors having been built prior to the emergence of mass movements against and stricter regulation of nuclear power. Sources of longitudinal variation are not explicitly modeled because (1) they do not relate to the hypothesis being tested and (2) there is sufficient within-year dispersion in design characteristics to generate well powered estimates.

In the second step of the analysis, I generate the predicted values of a reactor's lead time conditional on its design characteristics, type of reactor, and M_i while omitting the country and year fixed effects. This represents a measure of a reactor's expected lead time in a hypothetical "average country" and "average year" conditional on its design characteristics.

I regress these expected values of lead time on country-level characteristics. Past research has found that nations with higher GDP per capita tend to complete their NPPs faster *ceteris paribus* (Csereklyei et al., 2016). In light of the strong correlation of GDP per capita with political institutions (Acemoglu and Robinson, 2012), I control for the natural log of GDP per capita in order to avoid any possible spurious correlation between level of economic development and form of government. I estimate the following equation by ordinary least squares:

$$ln(\widehat{LT_i}) = \beta_1 ln(GDPpc_{c,y}) + \beta_2 Dem_{c,y} + \beta_3 Dec_{c,y} + \varepsilon_i \tag{1.4}$$

This regression tests whether economic development and political institutions are associated with choices in the design of NPPs that entail longer or shorter lead times.

1.3.2 Modeling Mechanism 2: Regulatory Delays

I hypothesize that political decentralization generates conditions that cause construction to be temporarily halted or to proceed more slowly than would otherwise occur. This hypothesis proposes that, on average, otherwise identical reactors built in politically decentralized nations will tend to take longer to build than those in politically centralized nations, holding all else constant. The difficulty is in credibly identifying "otherwise identical reactors."

To begin, I include fixed effects for the model of reactor. I argue that this is a sufficient control for reactors which are of a standardized design ($n = 311$), which share a common designation supplied by the lead designer of the NSSS. Eight pairs of reactors built as twins at the same site are classified with a unique model name, although they are not classified as standardized because they were never replicated elsewhere. As a general rule, twin reactors at the same site are identical. This group presents no econometric concern but offers no cross-country variation to exploit. Reactors of models that were only built once ($n = 50$) are automatically dropped by the estimation procedure due to misleading causal inference that arises from singleton fixed effects (Correia, 2015).

The more challenging case is that of non-standardized "models" of reactors that have been built in more than one country ($n = 212$). To account for the technically differing features of non-standardized models that may cause them to have shorter or longer lead times, I control for the predicted lead time (conditional on design characteristics) that was generated in Step 1 of the procedure outlined in Section 1.3.1. This approach maintains the parsimony of the econometric specification, as contrasted with controlling for several dozen design characteristics. Furthermore, while the design characteristic data cannot be publicly released due to IAEA data sharing restrictions, no such restriction applies to the predicted values of lead time I generated from them by Equation 1.3. Thus, the data necessary to replicate this analysis have been made available.

I omit country fixed effects for two reasons. First, within-country, over-time variation in decentralization is exceedingly limited when considering how few countries have built nuclear power plants entirely before and entirely after major changes in their political institutions. Second, the cross-national variation in decentralization is of greater interest, as cross-national differences in nuclear power plant lead time is the primary puzzle. Since the treatment of interest–political decentralization–is more or less assigned by country rather than by reactor, the standard errors are clustered by country.

I do not include year fixed effects. Instead, I explicitly model the major events that are widely believed to have caused lengthy delays, per the instrumental variables methodology described in Appendix B.4. The controls for these events take the form of binary indicator variables that indicate whether a reactor was under construction during a given event. I further allow a separate coefficient for the nations in which the accident occurred, namely the United States in the case of TMI and the Soviet Union in the case of Chernobyl.[20]

Lastly, I control for whether the reactor was built for an investor-owned or publicly-owned utility.[21] Several possible hypotheses may point toward one form of ownership structure favoring faster or slower construction given the differing economic incentives, regulatory treatment, and cost of capital associated with each business model. My preferred hypothesis

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[20] No such interaction term can be estimated for Japan, as the two reactors under construction in Japan on 3/11/2011 have not been completed.

[21] In the case of fractional ownership among multiple utilities, I code the variable according to the ownership structure of the lead utility.

is that, given the higher cost of capital for investor-owned utilities, I expect that investor-owned utilities generally complete construction faster.

The econometric model is given by:

$$\begin{aligned} ln(LT_i) =& \beta_1 ln(GDPpc_{c,y}) + \beta_2 Dem_{c,y} + \beta_3 Dec_{c,y} \\ &+ \sum_{x \in X} \xi_{x,i} + \gamma_1 \mathbb{1}\{IOU_i\} + \gamma_2 ln(\widehat{LT_i}) + \lambda_m + \varepsilon_i \end{aligned} \tag{1.5}$$

1.3.3 Modeling Mechanism 3: Megaproject Syndrome

Megaprojects such as nuclear power plants have a natural tendency toward schedule slippage. I theorize that political decentralization exacerbates megaproject syndrome by initiating more instances of scope change mid-construction and increasing the number of external stakeholders who may intervene in the project.

To quantitatively measure such an effect, I take as a measure of complexity and scale the variable $ln(\widehat{LT_i})$ generated from Step 1 of the analysis in Section 1.3.1. This variable primarily reflects the size of the reactor in megawatts, but it also incorporates several other specifications and design choices that are associated with longer or shorter lead times, such as whether the reactor is of a standardized design. I hypothesize that, if decentralization exacerbates megaproject syndrome, then the penalty to lead time arising from a higher degree of "megaproject-iness" should be stronger in decentralized nations. I model this with an interaction between $ln(\widehat{LT_i})$ and decentralization.

I build the econometric specification as follows. I include country fixed effects, as there is sufficient within-country dispersion in $ln(\widehat{LT_i})$ to generate well-powered estimates. These fixed effects control for differing national characteristics; cross-national differences in the level of LT are not of interest for this hypothesis. Next, I include year fixed effects as there is sufficient dispersion within years to generate well-powered estimates. This removes any global time trends in LT.

However, two-way fixed effects cannot account for the possibility that time trends differ by country for reasons unrelated to the interaction of $ln(\widehat{LT_i})$ and decentralization. While fixed effects by country-year would be ideal, the number of degrees of freedom would greatly diminish with the introduction of so many fixed effects. Furthermore, in 155 cases, there were no other reactors which began construction in the same country in the same year, so there is no dispersion in size within those country-year pairs. As a next-best control for the possibility of differential trends by country, I include instrumented indicator variables for events which likely had a disproportionate effect on a particular country (TMI in the United States, Chernobyl in the Soviet Union)[22] or which occurred in different countries at different points in time (regime change). I also control for GDP per capita, which exhibits differing time trends across countries.

I do not control for any design characteristics or measurement error M_i, as these variables are embedded in the value of $ln(\widehat{LT_i})$. I do control for whether a investor-owned or publicly-owned utility is building the reactor, for the same reasons as in Section 1.3.2. I test several specifications, so the equation that follows is of a generalized nature, allowing for several specifications of β:

$$ln(LT_i) = \beta ln(\widehat{LT_i}) + \gamma_1 ln(GDPpc_{c,y}) + \gamma_2 \mathbb{1}\{IOU_i\} + \sum_{x \in X} \xi_{x,i} + \delta_f + \mu_c + \nu_t + \varepsilon_i \quad (1.6)$$

In the first specification, β is simply a constant that estimates the global average relationship between "megaproject-iness" and lead time. In the next specification, I allow β to vary as a linear combination of a nation's democracy and decentralization. While my hypothesis concerns decentralization, the intensity of megaproject syndrome could just as well vary with the level of democracy as with decentralization. Therefore, I include both variables in estimating β. In the final specification, I estimate separate values of β by geopolitical region, as defined in Table 1.1.

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[22] No reactors under construction as of 3/11/2011 have entered operation in Japan as of the time of writing, so the parameter cannot be estimated.

1.3.4 Modeling Mechanism 4: resetting the learning curve

I theorize that political decentralization inhibits learning-by-doing through regulatory instability, jurisdictional diversity, and electricity market fragmentation. These factor oblige firms to abandon gains from proceeding down an established learning curve and begin exploring the learning curve of a more novel design. To estimate this effect empirically, I propose an econometric specification that allows the learning rate to vary according to the degree of decentralization of a country's political institutions.

I operationalize cumulative experience as the inverse hyperbolic sine transformation of the count of reactors of the same family as reactor i that began construction prior to reactor i. Further details regarding the measurement of cumulative experience are available in Appendix B.5.

I distinguish between two possible dimensions along which experience may matter. The first is the *within* dimension: the effect of cumulative experience on lead time that results from continuing to build more reactors *within* the same family. The second is the *between* dimension: the effect of cumulative experience on lead time that results when choosing *between* families of reactors with differing levels of cumulative experience.

I argue that the between dimension contains information regarding "learning-by-searching" (Cohen and Levinthal, 1989), as opposed to learning-by-doing. When utilities are deciding between different designs of NPP to build, they face choices ranging from experimental reactor designs of uncertain future potential to reactor from families with an established track record and large experience base to draw from. The more established design should, in expectation, present fewer challenges in the construction process—even if the less experienced design has a greater, long-term techno-economic potential (Cowan, 1990). In settings with weak, inefficient, or impeded learning-by-searching, the benefits to adopting a more established design should be less evident.

In both cases, the methods herein do not generate strong causal inference. They should be understood as descriptive partial associations between cumulative experience and lead time, holding constant several other factors that might otherwise explain the correlation between experience and lead time. In particular, because cumulative experience is endogenous—families that are inherently better for techno-economic reasons are liable to gain more experience—estimation along the between dimension is especially suspect. Improving causal inference is an opportunity for future research.

For the econometric specification to capture "within family" learning, I naturally include fixed effects by reactor family. This means the econometric model assumes there are constant, unexplained differences between the level of lead time across different reactor families. Next, I include country fixed effects.[23] Political factors may cause differences in the average level of LT across countries; these differences are investigated with the methods of Section 1.3.2 but are not of interest here.

These sets of fixed effects combine to form an econometric specification in which the only remaining variation to be explained is changes in LT over time, within families of reactors, controlling for cross-national average differences in the level of lead time. Fixed effects by year of construction start would sap the model of nearly all remaining variation. Instead, I control for the major events affecting the nuclear industry per the instrumental variables strategy laid out in Appendix B.4.

In general, I do not control for design specifications in these regressions, because an important component of learning-by-doing is using the information gained to redesign the product better next time. Holding design constant would limit the estimated learning effects to only learning arising from repetition of of identical or nearly similar designs. That said, I make three exceptions in controlling for the following design specifications:

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[23] Where country is defined as the country in which construction began. E.g. the Soviet Union and Russia are two separate "countries" for this purpose. Reactors which began construction under the Soviet Union and finished after its collapse are coded as belonging to the Soviet Union.

First, I control for rated power output in megawatts. The trend towards increasingly large reactors over time is unambiguous; furthermore, size tends to be correlated with a reactor family's cumulative experience. In a regression of size in megawatts on cumulative experience with year fixed effects (i.e. removing any time trends and only looking at cross-sectional variation), I find that a doubling of cumulative experience is associated with a 74 megawatt increase in the size of a reactor ($t = 10.1$). In other words, new concepts for reactors are implemented at a small scale first and then gradually scaled up as experience accumulates.

Given the economic costs of long lead times, I must conclude that NPP designers are not deliberately choosing larger capacities for the sake of longer lead times. Instead, they are reportedly choosing larger capacities in order to reduce OCC. Berthélemy and Escobar Rangel (2015) find a strong negative association between size and OCC when controlling for LT; in unreported regressions, I replicate that finding with the larger sample provided by Portugal-Pereira et al. (2018). However, given the likely causal effect of LT on OCC and the certain effect of LT on financing costs, this strategy of ever-increasing scale may not be wise.

Two additional design characteristics I control for are whether the reactor was used for co-production of electricity and plutonium and the cooling technology. I argue that reactors which co-produced electricity and plutonium exhibit exceptionally fast lead times because they were built in haste for military purposes during the Cold War. Regarding cooling technology, the use of once-through cooling or some other method to discharge waste heat is determined by environmental conditions and environmental regulations. Cooling towers are not unique to the nuclear industry.

As in Sections 1.3.2 and 1.3.3, I control for whether the reactor is being built for an investor-owned or publicly-owned utility for the same reasons described there. Given the substantial within-country, over-time variation in GDP per capita, I control for it. Conversely, there is very little within-country, over-time variation in the level of democracy and decentralization in my sample, so I do not control for those. To summarize, the econometric specification for "within family" learning-by-doing is given by:

$$\begin{aligned} ln(LT_i) =& \beta sinh^{-1}(Exp_{i,f}) + \theta_1 MW_i + \theta_2 \mathbb{1}\{OTC_i\} + \theta_3 \mathbb{1}\{Pu_i\} + \sum_{x \in X} \xi_{x,i} \\ & + \gamma_1 ln(GDPpc_{c,y}) + \gamma_2 \mathbb{1}\{IOU_i\} + \gamma_3 M_i + \delta_f + \mu_c + \varepsilon_i \end{aligned} \tag{1.7}$$

Similar to the approach in Section 1.3.3, I allow β to vary across countries according to a linear combination of its political characteristics. I standardize $ln(GDPpc_{c,y})$, $Dem_{c,y}$, and $Dem_{c,y}$ such that they are centered on their global average values and scaled by their global standard deviations.[24]

To estimate the effects of cumulative experience when comparing between different families of reactors, the first step is to omit the family fixed effects. I retain the country fixed effects from before, as there is plenty of within-country dispersion in cumulative experience to work with. This time, I add year fixed across, so that the comparison is between different families of reactors with differing levels of experience at the same point in time. Year fixed effects render unnecessary most of the controls for major events affecting the nuclear industry, except those that may affect certain countries deferentially, as discussed in Section 1.3.3.

As with the "within family" estimation, I control for capacity in megawatts, plutonium co-production, investor-ownership, and GDP per capita. The econometric specification for "between family" learning-by-searching is given by:

$$\begin{aligned} ln(LT_i) =& \beta sinh^{-1}(Exp_{i,f}) + \theta_1 MW_i + \theta_2 \mathbb{1}\{OTC_i\} + \theta_3 \mathbb{1}\{Pu_i\} + \sum_{x \in X'} \xi_{x,i} \\ & + \gamma_1 ln(GDPpc_{c,y}) + \gamma_2 \mathbb{1}\{IOU_i\} + \gamma_3 M_i + \mu_c + \nu_t + \varepsilon_i \end{aligned} \tag{1.8}$$

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[24] Global averages and standard deviations are computed from the global population of countries, not just those which have built NPPs.

1.4 Results

1.4.1 Results for Mechanism 1: Politically Constrained Design

The estimation results of Equation 1.3—the regression of lead time on design specifications—is presented in Table 1.5. I will define the variables and interpret the coefficients for the benefit of readers not familiar with the technical terms related to nuclear reactor design.

The relationship between power output and lead time was ascertained to be best approximated as log-linear through rigorous testing of alternative specifications. The estimated effect size implies that a typical 1GW reactor (which is the approximate order of magnitude of nearly all reactors being built today) would take 70.6% longer to build than a hypothetical 50 MW small modular reactor (SMR). For reference, the global average LT for gigawatt-scale reactors is around 86 months, so the basis of the scaling factor alone, the estimated lead time of the SMR would be 50.4 months. Further applying the bonus to standardized designs brings the estimate to around 45.5 months.

Reactor outlet temperature refers to temperature of the primary coolant upon exit from the reactor.[25] The median reactor outlet temperature is 328°C. The minimum observed value is 220°C; the maximum of 950 °C. Hotter outlet temperatures enable greater thermal efficiency in the conversion of steam to electricity, but they also present greater safety challenges.

The number of primary coolant loops[26] do not vary quite so widely, being typically between two and four, with a maximum observed value of 8. The results suggest that more loops represent more complexity to deal with in construction, but the effect sizes are not statistically significant. That said, in unreported regressions I find there is a clear trend towards a reduction in the number of these loops, which is consistent with the idea of the industry

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[25] The primary coolant is the fluid that conveys heat away from the core, where the heat is generated, to the remainder of the plant where it is converted to steam.

[26] These are the independent piping systems through which primary coolant flows

Dependent Variable: $ln(LT_i)$

	Marginal Effect	(Standard Error)
100 MWe increase in power output	**5.7%**	(0.8%)
1°C increase in reactor outlet temperature	**0.16%**	(0.05%)
1 MPa increase in pressure of the primary coolant	**0.12%**	(2.0%)
One additional primary coolant loop	**3.2%**	(1.2%)
One additional reactor coolant pump/circulator	**0.2%**	(1.1%)
Once-through cooling to discharge waste heat	**-13.6%**	(3.4%)
Standardized reactor design	**-11.4%**	(4.1%)
M_i (see Appendix B.2 for interpretation)	**10.2%**	(2.2%)
Reactor Type Fixed Effects		
Pressurized Water Reactor *(reference category)*	—	(N/A)
Boiling Water Reactor	**-31.0%**	(12.1%)
Pressurized Heavy Water Reactor	**-11.4%**	(14.1%)
Gas-Cooled Reactor	**-26.1%**	(22.3%)
Light Water Graphite Reactor	**-25.6%**	(18.4%)
Other reactor designs	**-18.5%**	(23.8%)
Containment Design Fixed Effects		
Large Dry *(reference category)*	—	(N/A)
Subatmospheric	**-6.2%**	(12.7%)
Vacuum Building	**5.2%**	(15.0%)
Ice Condenser	**16.1%**	(11.2%)
Mark I	**58.4%**	(24.2%)
Mark II	**61.6%**	(26.3%)
Mark III	**57.7%**	(26.0%)
Other BWR Containment Design	**52.9%**	(26.2%)
No Containment	**49.8%**	(35.8%)
Other Containment / Missing Data	**59.5%**	(21.3%)
Country Fixed Effects	✓	
Year Fixed Effects	✓	
Observations	582	

Table 1.5: Marginal Effects of Design Characteristics on NPP Lead Time

Dependent Variable: 1 if the reactor is standardized, 0 otherwise

	(1)	(2)	(3)
GDP per capita	**1.98**	**0.96**	**5.23**
one S.D. increase in $ln(GDPpc_{c,y})$	(1.32)	(-0.10)	(1.62)
Democracy	**0.74**	**3.41**	**2.54**
one S.D. increase in Dem	(-0.99)	(3.23)	(2.20)
Decentralization	**0.97**		
1 if country has a federal constitution	(-0.05)		
one S.D. increase in $Dec_{c,y}$ (RAI)		**0.68**	**1.32**
		(-1.18)	(0.48)
Population			**2.72**
$ln(Pop_{c,y})$			(2.16)
Electricity Sector Fragmentation			**0.26**
$ln(NumUtil_c)$			(-2.00)
Investor-Owned Utility	**0.19**	**0.30**	**0.98**
IOU_i	(-2.46)	(-1.85)	(-0.03)
Time Trend	**1.12**	**1.17**	**1.09**
year construction began	(3.50)	(5.16)	(2.35)
N	773	626	626

Odds ratios in **bold.** (t-statistics in parentheses.)

Table 1.6: Predictors of Reactor Design Standardization

trying to streamline design.

Once-through cooling (OTC) refers to the practice of discharging waste heat directly into a nearby body of water. This obviates the need for cooling towers or other structures designed to dissipate waste heat into the atmosphere; it also enhances the efficiency of the conversion of heat to electricity. There is a sizeable reduction in lead time associated with OTC, approximately 12.5%. In unreported regressions, no statistical difference was found when comparing natural draft to forced draft cooling towers; both add nearly the same amount to the construction schedule relative to OTC.

I find that reactors of standardized designs finish construction and commissioning 11.4% faster than their custom-built peers, on average. This suggests that custom-ordering a nuclear power plant is generally a mistake, except perhaps for experimental purposes. To explore this further, I ran a logistic regression to understand the determinants of reactor standardization, the results of which are presented in Table 1.6. At first, it appears that decentralized nations and investor-owned utilities are less likely to adopt standardized designs (as indicated by odds-ratios less than one). However, Column (4) reveals that this finding is probably an artefact of the fragmentation of the electricity sector in such countries, and not necessarily related to political conditions. I theorize that countries with more utilities fail to coordinate on a standardized design.

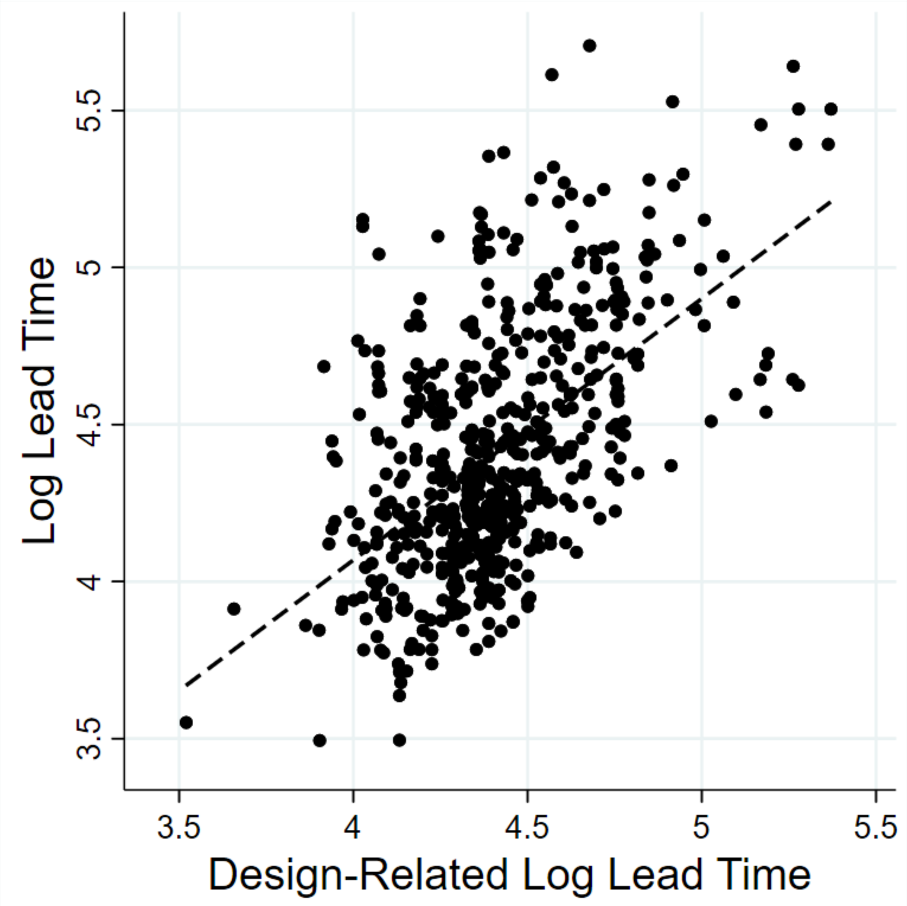

Figure 1.4: Goodness of Fit of Equation 1.3

The predicted values of LT generated after estimating Equation 1.3 are displayed in Figure 1.4, where they are graphed against the observed values of LT. The estimated slope coefficient is 0.832 (standard error = 0.072, N = 590). The R^2 of this bivariate regression–30.1%–implies that observed design characteristics only account for a modest fraction of the overall global dispersion in lead times. Furthermore, I find predicted LT does not meaningfully trend upward over time.[27] This is suggestive evidence for the view that the escalation over time in LT cannot be solely attributed to changes in design, whether arising from regulation or industry mismanagement. However, further research should revisit this question when more data concerning safety features can be collected.

Dependent Variable: $ln(\widehat{LT_i})$

	(1)	(2)	(3)
GDP per capita	**12.2%**	**13.1%**	**-2.15%**
one S.D. increase in $ln(GDPpc_{c,y})$	(1.79)	(1.51)	(-0.41)
Democracy	**1.11%**	**-0.35%**	**4.57%**
one S.D. increase in $Dem_{c,y}$	(0.40)	(-0.09)	(1.10)
Decentralization	**-0.31%**		
1 if country has a federal constitution	(-0.05)		
one S.D. increase in $Dec_{c,y}$ (RAI)		**0.12%** (0.03)	**-1.07%** (-0.23)
Capacity			**3.94%**
100 MWe increase in power output			(3.73)
Observations	612	513	513
adjusted R^2, overall	0.074	0.063	0.269

Transformed marginal effects on $\widehat{LT_i}$ in **bold.** (t-statistics in parentheses.)

Table 1.7: Estimation Results of Equation 1.4

Table 1.7 displays the results of the second stage of the analysis, wherein the fitted values of lead time (as predicted solely by design characteristics) are regressed on national characteristics. The only national characteristic meaningfully correlated with design-related lead time

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[27] A bivariate regression finds that predicted LT increased by less than 0.1% per year (p=0.77) over the sample period.

is GDP per capita, and this correlation becomes statistically and substantively insignificant when controlling for the tendency of richer countries to build larger reactors. This is strong evidence against the hypothesis of "politically constrained design." That is to say, there is no evidence that democratic or decentralized nations exhibit longer LT in NPP construction on account of differences in the design of the plants as compared to those in undemocratic or centralized nations.

1.4.2 Results for Mechanism 2: Regulatory Delays

In Table 1.8, I report the results of Equation 1.5. Columns (1) and (2) present estimation results as originally specified in Equation 1.5. The coefficients on the two measures of decentralization are statistically insignificant; that is, they fail to reject the null hypothesis of no relationship between decentralization and lead time, conditional on reactor model and other controls.

The null results arising from the estimation of both Equation 1.4 and Equation 1.5, at first glance, may appear to rule out two mutually exclusive and exhaustive channels by which political decentralization might correlate with NPP lead time. Either decentralization correlates with NPP lead time on account of differences in design, or decentralization correlates with NPP lead time holding design constant, or there is no correlation. However, as discussed in Section 1.2.3, there is, in fact, a meaningfully large and statistically significant bivariate correlation.

Hence, the question arises of "where did correlation go?" In Columns(3) and (4) of 1.8, I exclude the fixed effects by reactor model originally specified for Equation 1.5. The coefficients on decentralization become empirically large and highly statistically significant. From this, I conclude that the correlation was absorbed by the reactor model fixed effects of Columns (1) and (2). There are two possible interpretations of these findings:

Dependent Variable: $ln(LT_i)$

	(1)	(2)	(3)	(4)
Three Mile Island Accident	**17.7%**	**19.4%**	**20.1%**	**23.6%**
under construction on 3/28/1979	(3.20)	(2.31)	(4.13)	(3.10)
Three Mile Island Accident × USA	**37.0%**	**40.2%**	**31.4%**	**35.1%**
under construction on 3/28/1979 in the USA	(3.98)	(3.47)	(5.07)	(4.17)
Chernobyl Disaster	**2.8%**	**-2.5%**	**13.2%**	**6.0%**
under construction on 4/26/1986	(0.29)	(-0.22)	(1.92)	(0.85)
Chernobyl Disaster × USSR	**-31.6%**	*not*	**-31.7%**	*not*
under construction on 4/26/1986 in the USSR	(-2.92)	*estimable*	(-3.63)	*estimable*
Fukushima Daiichi Disaster	**-11.9%**	**-18.1%**	**9.9%**	**0.8%**
under construction on 3/11/2011	(-0.73)	(-0.86)	(1.49)	(0.10)
Regime Change	**31.8%**	**19.1%**	**50.3%**	**48.1%**
under construction during regime change	(2.39)	(1.04)	(3.13)	(2.10)
GDP per capita	**-0.9%**	**4.5%**	**-9.2%**	**-11.4%**
one S.D. increase in $ln(GDPpc_{c,y})$	(-0.20)	(1.34)	(-2.38)	(-2.34)
Democracy	**-4.1%**	**-6.9%**	**1.0%**	**0.4%**
one S.D. increase in $Dem_{c,y}$	(-1.50)	(-1.64)	(0.41)	(0.12)
Decentralization	**7.1%**		**22.6%**	
1 if country has a federal constitution	(1.08)		(5.00)	
one S.D. increase in $Dec_{c,y}$ (RAI)		**1.4%** (0.40)		**9.8%** (3.17)
Investor-Owned Utility	**-10.4%**	**-10.5%**	**-16.0%**	**-14.9%**
IOU_i	(-2.44)	(-2.44)	(-6.05)	(-3.41)
Expected LT, conditional on design	**0.85** %	**0.86%**	**0.68%**	**0.71%**
one percent increase in $\widehat{LT_i}$	(5.32)	(4.94)	(8.17)	(7.30)
Reactor Model Fixed Effects	✓	✓		
Observations	556	476	590	500
adjusted R^2	0.720	0.740	0.663	0.660

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

Table 1.8: Estimation Results of Equation 1.5

One possibility is that reactor model fixed effects behave approximately like country fixed effects, on account of the fact that certain models historically were only built in one country or a handful of geopolitically-allied nations. This would tend to sap the model of statistical power by limiting the cross-national comparison to relatively few cases where identical models were built in countries with large differences in their level of political decentralization.

The second possibility is that there are technical specifications that are unobserved in my dataset yet are relevant to the hypothesis of politically-constrained design. If this possibility is true, then it would mean that the null results in Table 1.7 are false negatives. Reactor model fixed effects are "black boxes" that absorb and contain the effect of any omitted technical specifications which have a bearing on NPP lead time.

In short, with the present data, it is impossible to distinguish between these two hypotheses—politically constrained design and regulatory delays—in ascertaining the channel by which decentralization correlates with NPP lead time. That said, we can reject the observed design characteristics listed in Table B.3 as explaining the correlation. Furthermore, the results Columns (3) and (4) present some reassurance that the raw correlation is not totally spurious, given the controls for nuclear accidents, regime change, GDP per capita, democracy, investor-ownership, and the expected lead time conditional on observed design characteristics.

The interpretation of the effect sizes in Columns (3) and (4) are as follows. A federalist constitutional design is associated with 22.6% longer lead time, relative to unitary constitutions. The range of globally observed values in the continuous measure of decentralization (RAI) spans approximately three standard deviations, so the comparable effect size from Column (4) would be on the order of a 30% increase. A 3-S.D. increase in decentralization is equivalent to the difference between federalism in the United States and the centralism in Finland present in the 1970s.[28]

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[28] Disregard the special autonomous status of the Åland Islands, where no NPPs have been built.

Table 1.8 also present results of the estimated effect on lead time arising from various events that impacted the politics and regulation of the nuclear industry. As these are not central to the present work, I will not discuss them at length. However, I will note a few issues that likely undermine the accuracy of the estimates. First, the finding that the Chernobyl disaster supposedly accelerated NPP construction in the USSR is almost surely spurious. Being under construction during the Chernobyl disaster in the USSR is correlated with being under construction during regime change, as the USSR dissolved a few years later. Per the results in Column (3), the combined effect of both events is roughly a 32%[29] increase in LT. Soviet NPPs which were under construction on 4/26/1986 but still finished construction prior to 1991 represent those which began their construction relatively earlier (recall that Eq. 1.5 includes no year fixed effects) and therefore were closer to completing construction sooner, thereby avoiding the upheaval of the 1990s.

Regarding the Fukushima Daiichi disaster, only reactors which have commenced commercial operation as of April 6th, 2021 are included in the sample, so the coefficient is necessarily biased downwards by the exclusion of as-of-yet incomplete reactors.

1.4.3 Results for Mechanism 3: Megaproject Syndrome

Table 1.9 displays the results of regressions which test the hypothesis that the impact of scale and complexity of design on NPP lead time is mediated by political decentralization. Column (1) reports the finding that, globally on average, the correspondence between a reactor's predicted LT and its actual LT is fairly close to a one-to-one relationship.[30] In Columns (2), (3), and (4), I allow the parameter governing this relationship to vary according to national political characteristics. Note that the $Dem_{c,y}$ and $Dec_{c,y}$ variables are standardized according to their z-values, so they are centered on the global averages. Thus, the uninteracted

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[29] $13.2\% - 31.7\% + 50.3\% = 31.8\%$

[30] The upper bound of the 95% confidence interval is 1.06.

Dependent Variable: $ln(LT_i)$

	(1)	(2)	(3)	(4)
Expected LT, conditional on design	**0.91%**	**0.89%**	**0.85%**	
one percent increase in $\widehat{LT_i}$	(13.04)	(12.62)	(11.03)	
Expected LT × Democracy		**-0.01%**	**-0.00%**	
... × one S.D. increase in $Dem_{c,y}$		(-0.47)	(-0.06)	
Expected LT × Decentralization		**0.03%**		
... × 1 if country has a federal constitution		(1.92)		
... × one S.D. increase in $Dec_{c,y}$ (RAI)			**0.01%**	
			(1.01)	
Expected LT × East Asia				**0.49%**
one percent increase in $\widehat{LT_i}$ *in East Asia*				(4.15)
Expected LT × Western Bloc				**0.97%**
one percent increase in $\widehat{LT_i}$ *in the Western Bloc*				(11.13)
Expected LT × Eastern Bloc				**1.06%**
one percent increase in $\widehat{LT_i}$ *in the Eastern Bloc*				(4.03)
Expected LT × Global South				**1.70%**
one percent increase in $\widehat{LT_i}$ *in the Global South*				(3.90)
GDP per capita	**-15.7%**	**-22.8%**	**-15.1%**	**-10.3%**
one S.D. increase in $ln(GDPpc_{c,y})$	(-0.95)	(-1.29)	(-0.92)	(-0.63)
Investor-Owned Utility	**-6.5%**	**-5.7%**	**-4.3%**	**-6.3%**
IOU_i	(-1.14)	(-1.00)	(-0.71)	(-1.13)
Reactor Family Fixed Effects	✓	✓	✓	✓
Country Fixed Effects	✓	✓	✓	✓
Year Fixed Effects	✓	✓	✓	✓
Nuclear Accidents & Regime Change	✓	✓	✓	✓
Observations	571	571	483	571
adjusted. R^2, within-effects	0.344	0.359	0.311	0.362

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

Table 1.9: Estimation Results of Equation 1.6

coefficient on $\widehat{LT_i}$ can be interpreted as the marginal effect in a country with average values of both variables.[31]

Columns (2) and (3) concur in rejecting the hypothesis that national political characteristics contribute to megaproject syndrome by sharpening the penalty to lead time that results from NPPs of larger and more complex designs. The results are both statistically insignificant and not of an economically substantive magnitude.

Column (4) allows for the relationship between $\widehat{LT_i}$ and LT_i to vary according to geopolitical regions, which are defined and justified in Appendix A.3. Some interesting patterns emerge, although I will note that the only coefficient which statistically differs from one[32] is the coefficient for East Asia ($t = 3.73$). It appears that East Asian countries—Mainland China, Taiwan, South Korea, and Japan—are exceptionally competent at managing large and complex NPP construction projects, much more so than the rest of the world. This may have something to do with their highly unitary political regimes, although surely that is not the only factor at play. It should not go without mention that all three of Western–aligned East Asian nations began their NPP programs under eras of weak or absent democratic institutions involving rule by military dictatorships (e.g. the regime Park Chung-hee in South Korea) or a single political party (KMT in Taiwan, LDP in Japan). The increasing political contestation of nuclear power policy in these now firmly democratic nations might dismantle the conditions that made their earlier NPP deployments so successful. However, if democracy matters, the present methods are not sufficient to identify any such effect.

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[31] There is one exception, namely in Column (2). Having a federal constitution is not normalized; it is a binary variable. The interpretation of the uninteracted coefficient is that of the marginal effect in nations with unitary constitutions.

[32] The t-statistics in Table 1.9 refer to the coefficient's statistical difference from zero.

1.4.4 Results for Mechanism 4: resetting the learning curve

Table 1.10 displays the results of regressions estimating the effect of cumulative experience on lead time. Columns (1) and (2) report the raw parameters that form a linear combination in estimating β in Equation 1.7. Recall that this equation is designed to capture learning-by-doing within reactor families by examining trends in LT, holding constant any level effect of the reactor family. Similarly, Columns (3) and (4) report the raw parameters that form a linear combination in estimating β in Equation 1.8. Recall that this equation is designed to capture learning-by-searching across reactor families by how reactor families with more experience fare in terms of LT relative to those with less experience, compared at the same years in history.

Because variables $Dem_{c,y}$ and $Dec_{c,y}$ are standardized according to their z-values, the uninteracted coefficient on cumulative experience can be interpreted as the marginal effect of experience within a country with average values of both variables.[33] The estimated learning-by-doing rate is not statistically different from zero in the average nation, whereas the benefit of learning-by-searching appears to be considerable. Averaging the two results in Columns (3) and (4) and transforming them according to Equation 1.1 implies a learning-by-searching rate of 6.1%. The interpretation is as follows: Consider two reactors from two different reactor families that are built in otherwise identical national conditions at the same point in time. Reactor A's family has a cumulative experience double that of reactor B's family. Holding all else equal, we expect the reactor A to finish construction 6.1% faster than reactor B. This may be because the family of reactor A is technically superior (hence why it has accumulated more experience) or it may be because of a greater experience base, which facilitates more timely construction. Future research could try to establish causal identification along this "between" dimension.

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[33] This is with the exception of Columns (1) and (3), as having a federal constitution is not normalized; it is a binary variable. The interpretation of the uninteracted coefficient is that of the marginal effect in nations with unitary constitutions.

Dependent Variable: $ln(LT_i)$

	(1)	(2)	(3)	(4)
Cumulative Experience	**0.005**	**-0.020**	**-0.073**	**-0.110**
$sinh^{-1}(Exp_{i,f})$	(0.15)	(-0.67)	(-3.39)	(-5.81)
Cum. Exp. × Democracy	**0.015**	**-0.000**	**0.029**	**0.009**
... × one S.D. increase in $Dem_{c,y}$	(1.79)	(-0.017)	(2.99)	(0.76)
Cum. Exp. × Decentralization	**-0.004**		**-0.048**	
... × 1 if country has a federal constitution	(-0.11)		(-1.76)	
... × one S.D. increase in $Dec_{c,y}$ (RAI)		**0.014** (1.37)		**0.019** (1.72)
Reactor Family Fixed Effects	✓	✓		
Year Fixed Effects			✓	✓
Country Fixed Effects	✓	✓	✓	✓
Additional Controls per Eqs. 1.7 and 1.8	✓	✓	✓	✓
Observations	595	503	601	509

Untransformed regression coefficients in **bold.** (t-statistics in parentheses.)

Table 1.10: Learning Parameters Estimated per Equations 1.7 and 1.8

Next, we examine the interaction terms and consider how these estimated learning rates vary according to political conditions. Columns (1) and (2) provide no support evidence for the hypothesis political decentralization mediates learning-by-doing. Columns (3) and (4) return coefficients with the opposite sign; neither are statistically significant at conventional levels. I conclude that there is no significant mediating role of political decentralization in learning-by-searching.

The result in Column (4) contrasts sharply with my finding in an earlier draft of this work, which reported a statistically significant ($t = 2.84$) parameter of 0.029 for the experience-decentralization interaction. To contextualize the magnitude of such parameter, I calculate that a nation with decentralization two standard deviations above the global average would experience a learning rate of -5.5% (i.e. lead time would *increase* by 5.5% for every doubling of cumulative experience). As compared to the earlier work, the finding published in Table 1.10 reflects the latest available data from the Regional Authority Index (Hooghe et al., 2016), which notably expanded data coverage to India and (Mainland) China, *inter alia*, in early 2021. In an unreported regression, I replicate the earlier finding by excluding India and China from the sample.

This is not to argue that China and India should be disregarded. Instead, I believe their influence on the result is itself a remarkable finding. Unlike most countries that have built nuclear power plants, China and India exhibit considerable within-country, over-time variation in decentralization according to the self-rule index constructed by Hooghe et al. (2016). In India, while the average is 2 standard deviations above the global mean, it ranges from a minimum of 0.5 to 3.3 standard deviations above the global mean. In China, observed decentralization ranges from 1.0 to 1.6, although the preponderance of observations are in the vicinity of 1.

China's degree of decentralization, while modest relative to federal countries such as the United States (2.1 S.D. above the global mean), Canada (2.1), West Germany (2.5), and

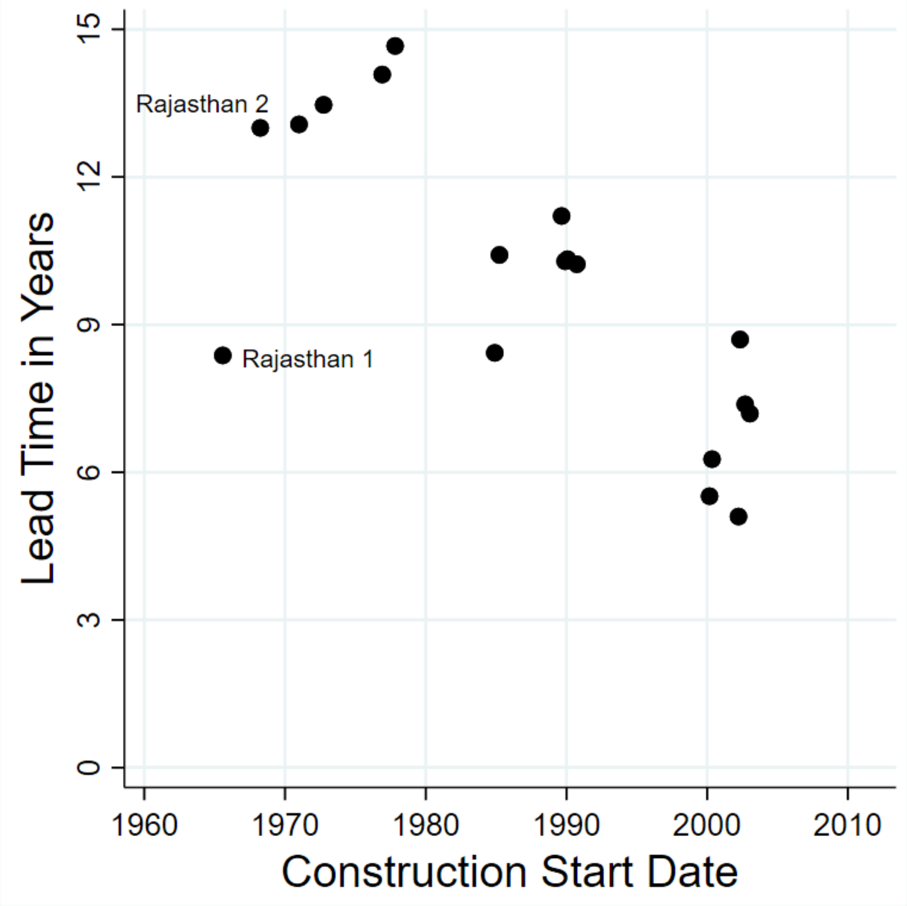

Figure 1.5: Lead Time for PHWRs in India

Switzerland (1.5), make it an outlier compared to its neighbors Taiwan (0.0), South Korea (-0.2), and Japan (0.6).

A final observation is the clear learning-by-doing trend in India's indigenous PHWR family, which I plot in Figure 1.5.[34] India is formally a federal nation; its federalism has deep historic roots; the data from the RAI are consistent with this. Thus, India's substantial reductions in lead time are stark evidence against the supposition that federalism is incompatible with progress in the construction economics of NPPs. Recognition of India's achievements is far from a novel contribution (Bohra and Sharma, 2006; Lovering et al., 2016), but I highlight

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[34] For historical context, I also include Rajasthan 1 & 2, although I classify them as part of the CANDU family, on account of the Canadian involvement in their design and construction. These were delayed due to the sudden termination of Canadian support in response to India's first test of nuclear weapons. I code all subsequent PHWRs in India as belonging to a separate family.

them here to acknowledge the challenge that India presents to my theory.

1.5 Conclusion

1.5.1 Discussion

This paper hypothesized and investigated several mechanisms by which decentralization influences the lead times of nuclear power plants. The findings are as follows:

The design specifications of NPPs, in so far as they relate to lead time, do not appear to be correlated with political factors. Richer countries have a tendency to build larger reactors. Decentralized countries have a higher propensity to build reactors of a non-standardized design, but this association is explained by their higher degree of electricity market fragmentation. Without a single national electric utility, coordination on a standardized design tends not to happen, except by explicit national policy, as in Japan.

Conditional on observed design specifications, I find that NPPs tend to take longer to build in politically decentralized nations. Further research is needed to improve the data coverage of safety-related technical characteristics of NPPs to ensure that the comparison is truly between "otherwise identical" NPPs. When the comparison is restricted to reactors of the same model built in different countries, the apparent partial association between decentralization and lead time disappears. One possible explanation for this result is that most reactor models appear in only one or a few similar countries, so the statistical power may be too weak to detect an effect.

I find that East Asian countries are unique in their capacity to manage construction NPPs with comparatively little penalty arising from of scale and more complexity. However, the evidence does not support the hypothesis that decentralization mediates the relationship between scale/complexity and NPP lead times.

The difference in the average learning-by-doing rate (effectively zero) and the average learning-by-searching rate (modest, but statistically significant and indicative of beneficial learning) merits some comment. The cross-sectional dimension and the time-dimension of the cumulative experience, as I have defined it, may reflect two different underlying data-generating processes. Over time, as more is learned about the technology of a reactor family, additional time-intensive measures become necessary to implement in reactor design in order satisfy new safety requirements or perhaps to improve operational reliability of the plant. This may be for reasons that simply trend upwards over time that are unrelated to learning about a specific technology, or perhaps it is a byproduct of learning. Empirically, I find increasing lead time for reactors built in decentralized nations as experience accumulates within reactor families, but no such effect in centralized nations. This is suggestive of a political explanation.

Conversely, at a given point in time, I find that there are clear gains to be had from choosing reactor families with more experience as opposed to less. If we suppose that political factors (like local opposition) are not sensitive to the details of the design of the plant, then it follows that such a relationship between experience and LT on the between dimension will not be mediated by political factors (which is what I have found empirically). I will conjecture, in absence of any evidence presented here, that local opposition to NPPs is generally not sensitive to the details of the design of a particular NPP and is instead motivated by generic concerns about the safety and sustainability of nuclear power.

Advocates of SMRs will find much to cheer in my work, as there are clear benefits to small size and standardized design with respect to lead time. Applying both the estimated scaling factor and the bonus from design standardization based on the result of Table 1.5, it can be conjectured that a 50 MW reactor of standardized design could achieve lead times on the order of 46 months. Such a lead time would go a long way toward improving the economics of NPP construction.

1.5.2 Directions for Future Research

I see several opportunities for extending and improving this area of research. In particular, more data on safety-related systems, structures, and components should be collected. IAEA PRIS and my supplementary data collection provided insufficient data coverage to incorporate such technical specifications into the analysis. Such data would generate greater confidence in the cross-national comparison of technically identical reactors without reliance on fixed effects. This would resolve the ambiguity regarding whether the correlation between decentralization and lead time is driven by differing design characteristics or other factors (such as regulation or construction sector productivity), irrespective of design.

A more clean-cut test of the "logic of local democratic control" would require direct measurements of the intensity of local opposition and regulatory burden on individual NPP construction projects. In Chapter 3, I conduct such an analysis for the United States. However, comparable measures of regulatory burden appropriate to the regulatory context of other nations would be desirable to improve the generalizability of findings.

The present work has largely taken the reactor family and the reactor model—as defined by the NSSS—as the primary unit of categorizing similar designs. However, NPPs consist of several other important features, such as the containment, the turbo-generator, and the balance-of-plant (BOP). Study of learning by firms involved other aspects of plant design and construction, such as the architect-engineer, the turbo-generator supplier, and the constructor could be another fruitful area for investigation. Berthélemy and Escobar Rangel (2015) show a clear role for the architect-engineer in learning, but the sample is limited to a handful of countries. More data collection on the identity of these firms could expand the analysis to the global population.

Another avenue for improvement would be to extend the present work by modeling the simultaneous determination of OCC and LT as in Berthélemy and Escobar Rangel (2015) while using the large sample of OCC data compiled by Portugal-Pereira et al. (2018). This would be important for determining the extent to which decentralization drives up OCC as a consequence of longer LT, or if it impacts OCC directly.

The results of Table 1.5 confirm past findings and conventional wisdom among industry observers that reactor standardization improves the economics of NPP construction. While I show that fragmentation of the electricity market is associated with non-standardization, the issue would benefit from more formal modeling of the decision to standardize. Indeed, why do firms ever redesign NPPs given the heavy upfront development and licensing costs? The answer surely involves regulation and learning, but there are likely to be industrial organization explanations for why customization was so historically prevalent in the U.S. nuclear industry.

The finding that East Asian countries suffer the least from megaproject syndrome in NPP construction, while nations of the Global South suffer the most, could be considered further. If not political decentralization, what attributes of these regions explain the difference? How can East Asian success be exported globally?

Chapter 2

Unbundling the Atom: nuclear power plant reliability in the neoliberal era

2.1 Introduction

Owners of capital equipment with low marginal operating cost should generally seek to maximize its utilization, provided that such utilization avoids a higher marginal cost from operating other capital equipment or profitably serves demand that would otherwise go unmet. It is on the basis of this principle that investment in expensive capital equipment is justified. However, in the absence of discipline by market forces, firms may neglect to utilize their capital efficiently. Such neglect may arise, for example, in a monopoly firm subject to rate-of-return regulation, whereby the profit they earn is the rental rate of "prudently invested" capital, rather than a function of the efficiency of current operations.

The global wave of restructuring, liberalization, and deregulation of industries formerly thought to be natural monopolies (or otherwise in need of economic regulation) has given new emphasis to the aforementioned principle. For example, deregulation has set the stage for substantial improvements in capacity utilization in the American trucking (Hubbard, 2003) and airline (Dana and Orlov, 2014) industries. In the context of the electricity sector, Davis and Wolfram (2012) find dramatic improvements in the capacity utilization of US nuclear power plants that were divested and operated in competitive wholesale markets, as compared against those which remained vertically integrated under the ownership of either regulated, privately-owned utilities or government-owned utilities.[1]

I extend the work of Davis and Wolfram (2012) to a nearly complete global sample of nuclear power plants. This provides an empirical setting with more variation in the timing of the treatment and a broader array of liberalized market structures. I find that liberalization in the United States and Canada is associated with large improvements in reliability for nuclear power plants, but modest or no improvements elsewhere in the world.

[Say more about persistent, unexplained gaps in capacity utilization across countries]

2.2 Prior Literature and Theory

2.2.1 Electricity Sector Restructuring

Prior literature has found evidence predominantly in favor of the view that restructuring and liberalization enhances the efficiency of the electricity sector. Privately-owned power plants operating in restructured U.S. markets reduced operating expenses (Fabrizio et al., 2007) and emissions (Chan et al., 2017) more than privately-owned power plants in regulated markets. U.S. coal plants divested from ownership by regulated utilities exhibit reductions in prices paid for fuel through more efficient procurement strategies and a lower propensity to

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[1] American readers may be more familiar with the terms “investor owned utility” (IOU) and “publicly-owned utility” (POU). I avoid these terms due to potential confusion with “public utility” (which refers the utility’s function in providing a public service) and “publicly traded” utility (privately-owned utilities may or may not be publicly traded).

adopt capital-intensive pollution abatement technology (Cicala, 2015). However, issues such as market power (Mansur, 2008) and the distribution of surplus and rents (Borenstein and Bushnell, 2015) are a persistent source of debate over the merits of restructured electricity markets.

The literature has been largely focused on the United States, in part because of the natural quasi-experiment arising from (A) the differential timing of restructuring on a state-by-state basis, (B) the absence of restructuring in some states, and (C) the presence of government-owned utilities, which form an additional control group. The literature on non-U.S. settings returns qualitatively similar findings. Indian states which unbundled their publicly-owned, vertically-integrated utilities by transferring management of their power plants to autonomous, corporatized (but still state-owned) generating companies benefited from a 25% reduction in forced outages and 10% increase in availability at their coal-fired plants (Malik et al., 2015). The restructuring and privatization of Britain's Central Electricity Generating Board (CEGB) resulted in an estimated 5% reduction in costs, including through improvements in operating efficiency of generators, fuel switching away from uneconomic domestic coal, and less capital-intensive investments in new generating capacity (Newbery and Pollitt, 1997). However, due to the initial divestiture of generating assets to too few firms, the exercise of market power meant that these costs savings were not passed on to customers, although this was later remedied (Newbery, 2006). In Turkey, during the privatization process from 2009 to 2013, wholesale power prices declined by 10% while retail rates increased by 5.8%, leading to public dissatisfaction with the results (Karahan and Toptas, 2013).

For a comprehensive review of the successes, failures, institutional details, and ongoing issues in restructured electricity markets, the reader is directed to Joskow (2008), who draws on both U.S. and international experience. Suffice it to say that "electricity sector restructuring" entails different policies and different market structures in different countries. Below, I outline a broad typology of reforms as they relate to generation and elaborate their theorized impact on nuclear power plant reliability.

A typical first reform in the restructuring process is unbundling, the formal separation of entities involved for generation from those involved in other segments of the electricity supply chain. This type of reform is motivated by the theory of soft and hard budget constraints (Kornai, 1986). An organizational unit purely engaged in generation is thought to be subject to greater transparency and accountability about its production, output, revenue and costs. This should make it easier for regulators or owners to oblige that entity to cover its costs with revenues from generation, rather than relying on state aid or cross-subsidization from other parts of the business.

Privatization is conceptually distinct from unbundling. Vertically-integrated utilities can be privately-owned; state-owned utilities can be unbundled while remaining public property. Privatization is theorized to increase efficiency of firm operations as a consequence of the profit motive. However, if a privately-owned firm remains a regulated monopoly, it may not be the residual claimant on increased output or decreased costs, which dulls the incentive for firm managers to identify and implement opportunities for efficiency improvements.

Unbundling may or may not be economically meaningful if the the unbundled generation entity is still owned, in whole or in part, by an entity that also owns transmission and distribution assets. For example, Korea Electric Power Corporation (KEPCO) was formerly the vertically-integrated, state-owned, national electric utility of South Korea. In 2001, its generation and assets were unbundled into several companies in preparation for further liberalization of the electricity market. However liberalization stalled; Korea Hydro & Nuclear Power (KHNP), which owns and operates South Korea's hydroelectric and nuclear power plants, today remains a wholly owned subsidiary of KEPCO (KNHP, n.d.). This sort of unbundling is termed “legal unbundling;” there are distinct legal entities but ownership remains in the same hands. Without vigilant regulation or the discipline of market forces, legally unbundled entities may still behave like a vertically integrated firm by, for example, coordinating to use its control of the transmission system to provide favorable dispatch of a corporate affiliate's generation at the expense of competitors' generation.

The creation of wholesale electricity markets relieves regulators of the need to closely monitor the costs and output of power plants to determine whether firms are managing and maintaining them optimally. The first fundamental theorem of welfare economics predicts that the invisible hand of the market will guide self-interested, price-taking firms to the optimal allocation of resources. However, the techno-economic features of electricity generation allow for substantial departures from the theoretical ideal of perfect competition. Power plants and transmission lines have capacity constraints in the short run and even medium run; capacity adjustment requires years, by which time the opportunity for one firm to undercut another firm's anti-competitive behavior may have disappeared. Anti-competitive behavior in wholesale electricity markets is well-documented (Wolfram, 1999), even at seemingly low levels of market concentration (Borenstein, 2002). Additionally, in the absence of reforms to retail pricing of electricity, electricity demand is highly inelastic in the short run, which increases the scope for monopolistic pricing.

2.2.2 Nuclear Power Plant Operational Performance

The earliest literature on the operational performance of NPPs exhibits considerable debate over the nature and causes of low capacity factors, averaging 62.3% globally in the 1970s.[2] An article in the *Bulletin of the Atomic Scientists* rhetorically asked, "Will Idle Capacity Kill Nuclear Power?" (Comey, 1974). Considerable debate was waged over the interpretation of the scarce data available at the time (Margen and Lindhe, 1975; Komanoff, 1976; Joskow and Rozanski, 1979b), but we now know—with the benefit of fifty years of hindsight—that the earliest decades of the industry were not representative of future performance. The capacity

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[2] Author's own calculations from PRIS.

factor of nuclear power plants today vastly exceeds that of any other generating technology in nearly every country in which they operate.

The high capacity factor of nuclear power plants is partly a consequence of the merit-order effect—the lower a plant's marginal cost of generation, the greater the priority with which it is dispatched to meet demand. Thus, a high capacity factor is a strong indicator of an efficient and reliable nuclear power plant, except in a handful of jurisdictions such as France where nuclear generating capacity will at times exceeds demand, forcing reductions in output.

However, the logic of the merit order cannot explain changes in capacity factor over time because the ranking of nuclear power within the merit order has never changed, even as the relative prices of uranium, coal, and natural gas have fluctuated over the decades. Rather, the capacity factors we observe today—in excess of 90% and approaching the theoretical maximum of 100%—were made possible by dramatic improvements in reliability. These include:

Shorter refueling outages. Most (but not all) designs of nuclear power plants require the plant to not operate when replacing spent fuel with fresh fuel. In the United States, the average duration of refueling outages has fallen from a high of 80 days in 1997 to 33 days in 2017 (EIA, 2018).

Fewer unplanned outages. An unplanned outage is a period of non-operation typically caused by the malfunction or deterioration of a plant component or system. Improved maintenance and learning-over-time about best practices can result in fewer unplanned outages.

Regulatory environment. In earlier decades, when nuclear power was technologically immature and regulations were being developed and revised to address newly discovered safety issues, regulatory interventions were a relatively more common cause of non-operation as compared to today.

A learning-by-doing effect in the operations of nuclear power plants (NPPs) was first postulated and tested by Joskow and Rozanski (1979b). With the benefit of more years of data to look back on, Lester and McCabe (1993) compare France and the United States in their learning about NPP operational performance. Their analysis attributes France's higher reliability (at that time) to France's greater standardization in reactor design and the industrial organization of the French electricity sector (as a single national monopoly), facilitating transfers of lessons learned across NPP sites. However, circumstances have since reversed the comparison. From 2009 to 2018, availability factors of NPPs averaged 92% in the United States and 73% in France.

2.2.3 Nuclear Power Plants in Restructured Electricity Markets

The seminal work on the performance of NPPs in restructured electricity markets is Davis and Wolfram (2012). Using monthly panel data of US nuclear power plants from 1970 to 2009 and daily panel data from 1999 to 2009, they estimate a 10% increase in output by divested NPPs relative to non-divested NPPs. This is largely attributable to greater uptime—particularly shorter outages—but also to a greater magnitude of uprates.[3] Their back-of-the-envelope calculations estimate that this improvement in output corresponds to additional revenue of approximately $2.5 billion (2012 dollars), of which approximately 14% is offset by increased operating costs and capital additions. Additionally, they estimate that the attendant displacement of fossil fuels reduces carbon dioxide emissions by about 35 million tons per year.

Given the large private and external benefits associated with improvements in NPP output, it is worth asking why large cross-country disparities in NPP operational reliability persist. I investigate the possibility that unique features of electricity sector restructuring in the

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[3] Uprates are changes to equipment and operations, authorized by safety regulators, that enable a higher capacity rating, i.e. greater power output.

United States explains a substantial part of the difference. I hypothesize that reforms which make NPP owners the residual claimant on increased revenue and avoided costs will have the strongest positive effect on operational performance.

2.3 National and Subnational Histories of Electricity Sector Restructuring

To construct the treatment variables, I reviewed a variety of sources to ascertain the ownership, regulatory, and market structure of electricity sector for each of the 38 countries which appear in the sample. For the United States and Canada, the research was conducted at the state and provincial level. Special attention was paid to the status of nuclear power plants, as their original arrangements and ultimate fate frequently differ from those of other types of generation. Sources reviewed include academic literature, reports of international intergovernmental bodies (IAEA, IEA, OECD NEA), industry news articles, and the websites of the relevant governments and utilities. The sources are cited in Appendix A.4.

Below, I discuss the methodology by which I encoded qualitative narratives of electricity sector restructuring into categorical variables with specific dates indicating when a reform enters into effect. A file providing the variable coding, dates of reform, sources cited, and discussion for every country and reactor is available with the online data appendix. Here, I provide a discussion of key trends and patterns that emerge from these data that will be relevant to the analysis.

2.3.1 Encoding of Restructuring Variables

For each reactor, I encode three variables representing the following aspects of the electricity sector: (1) vertical integration, (2) public or private ownership, and (3) competitive wholesale markets.

The variable for vertical integration can take on one of four possible values. A reactor is coded as bundled if it is owned and operated by an entity that is also directly involved in any regulated activity. Regulated activities include transmission and distribution in all cases; this may also include retail energy supply in cases where it is still regulated and bundled with generation. A reactor is coded as legally unbundled if it is owned by an entity that is also involved in any regulated activity but management of regulated activities and competitive activities is kept at arms-length through strict legal separation. This is typically achieved by converting the formerly vertically integrated utility into a holding company of several legally distinct subsidiaries. In the European Union, where this arrangement is most prevalent, subsidiaries operating in the regulated sectors (transmission and distribution) are subject to strict regulatory requirements to ensure non-discriminatory access to the grid and forbidding unfair sharing of information with affiliates in the competitive sectors.

A reactor is coded as ownership unbundled if it is owned by an entity that is not involved in any regulated activity in the jurisdiction where the reactor operates. This definition allows for the possibility that a firm might own regulated assets in another jurisdiction but effectively operate as an fully divested independent power producer in the jurisdiction of the reactor of interest. An example of this includes Électricité de France (EDF), which purchased several British nuclear power plants in 2009. EDF operates in a competitive British wholesale and retail markets but has no interest in British transmission or distribution assets; meanwhile, EDF's reactors in France supply energy at regulated, cost-of-service rates to French households and small businesses.

A final possible coding for the vertical integration is leased. This only characterizes the eight reactors at Bruce Nuclear Generating Station in Ontario Canada. Further description of this arrangement is provided in section 2.3.2 All of the firms that own Bruce Power share the characteristics of ownership unbundled firms in the sense that they do not also own regulated assets in Onatrio's electricity sector. Except where specified, leased is treated as identical to ownership unbundled because of the limited statistical power of using these 8 reactors, all of which are jointly managed at a single firm at a single site, to estimate the effect of leasing separately from any other arrangement.

The variable for public or private ownership of a reactor is binary in nature, taking on the values majority public and majority private. In case of an exact 50/50 split, ties are broken by the ownership type of whichever company is the listed as the operator in IAEA PRIS. If the operator is a third company specifically dedicated to operating the plant which is itself owned in an exact 50/50 public/private split, this variable takes the value "private."[4]

The crude nature of this coding was a result of several limitations and difficulties in the sources available. Many utilities and reactor holding companies experienced several changes in the exact distribution of ownership shares over a period of decades; few sources were found that reliably recorded this for reactors with a complex ownership histories. The challenge proliferates when a plant has several owners, one or more of which may be partially state-owned. The data that were most frequently available in the historical sources were the dates of large-scale privatizations, particularly those when the plant's ownership switched from majority public to majority private.

Therefore, I chose to limit the analysis to this binary measure, as it could be most reliably established for all plants in the sample. This can be partly justified by the following theoretical prediction: in cases where private and public interests in the management of a company

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[4] This final tie-breaking procedure was employed in a single case: Santa maría de Garoña, a single BWR in Spain.

conflict, the preferences of the majority of shareholders will prevail. However, there are good reasons to expect that the degree of public ownership matters, even when it is inframarginal to the issue of a majority shareholding. For example, several historical sources in Germany make reference to the power of *länder* to appoint directors to the boards of utilities in which the *land* is a minority shareholder. Conversely, one might hypothesize that privatization of a minority stake in a utility exposes it to some accountability and fiscal discipline that is not felt by a non-for-profit utility that functions as a department of a municipality, region or national government. Gathering historical data on the precise share of state ownership of nuclear power plants is an opportunity for further research.

The variable for wholesale markets may take on one of two possible values: competitive if the reactor operates in a jurisdiction where generation has open access to the transmission system and dispatch is decided by competitive markets managed by an independent entity, or uncompetitive. Negotiated third-party access to the transmission system and the ability to conduct bilateral trades are insufficient to be categorized as competitive by this scheme. In instances where various product markets are introduced at different times (e.g. real-time balancing, day-ahead energy markets, capacity markets, ancillary services), I take the first date of operation of day-ahead energy markets as the date on which this variable switches from uncompetitive to competitive.

The data for the outcome of interest (reliability) is recorded on a monthly basis. Thus, if a restructuring variable changes its status on a date other than the first of the month, there is some ambiguity as to how to accurately encode the variable. If the effective date of the reform is prior to the 15th day of the month, I encode the reform as having changed the variable to a new coding in that month. If the effective date of the reform is on or after the 15th day of the month, I encode the reform as having changed the variable to a new coding in the following month.

2.3.2 Discussion of Key Trends and Patterns

The coding of every reactor on each of these variables is available in the data appendix, along with notes explaining coding decisions in potentially ambiguous cases. This section will provide an overview of key trends and patterns that emerge from the data that will be relevant for the analysis.

Few countries exhibit subnational variation in the original or restructured industrial organization of their nuclear power plants. The primary exceptions to this pattern are found in the Anglophone countries: the United States, Canada, and the United Kingdom. In North America, subnational variation arises due to the federalism. The history of this is sufficiently for the United States by Davis and Wolfram (2012).

In Canada, several unique developments in the electricity sector are worth mentioning. The province of Ontario is home to all but 3 of Canada's nuclear reactors; these were constructed for and operated by the integrated, provincially-owned utility Ontario Hydro. In April of 1999, Onatrio Hydro was unbundled but not privatized; the new organization running the provinces NPPs was named Ontario Power Generation (OPG). In May 2001, OPG leased one of its three plants—accounting for 8 of its 20 reactors—to Bruce Power, which is a partnership of several privately-owned corporations, labor unions, and a provincial pension fund. Bruce Power receives a long-term, contracted price per MWh generated. It has borne the expense of several costly refurbishments to bring mothballed units back into service and by all accounts is the residual claimant on increased output and decreased costs.

In Québec, the provincially-owned utility Hydro-Québec has minimally unbundled its transmission system to comply with FERC rules in order to export to U.S. electricity markets. However, competitive wholesale markets have not been formed and the remainder of the system has not been liberalized. New Brunswick, which is home to a single reactor, fully unbundled its provincial utility in 2003 but vertically reintegrated it in 2013. This is the sole case of rebundling found in the sample. Like Québec, New Brunswick has never established competitive wholesale electricity markets.

In the United Kingdom, subnational variation existed temporarily between 1990 and 1996—Scottish NPPs were held by an unbundled, state-owned entity separately from the English and Welsh plants.[5] The only difference between the Scottish and English-Welsh electricity sector during this time was the existence of wholesale spot markets in England and Wales and their absence in Scotland. This arrangement was revised in July of 1996 when the nuclear holdings were re-arranged on the basis of plant design rather than geography; plants of the older MAGNOX design were retained by a state-owned company while plants of the newer AGR designs and one PWR were privatized.

The assignment of British reactors to one treatment or the other is the primary impediment to credible causal identification, as the assignment is clearly non-random. A cross-national comparison of British nuclear is also stymied by the relative rarity of gas-cooled, graphite-moderated reactors (abbreviated simply GCR)[6] most common in Britain. While France built ten such reactors (including one in Spain), none are comparable in age to British AGRs ("advanced GCR") and all of them were retired prior to or during the early nineties. Two British-designed GCRs were built outside Britain: one in Italy, which was forced to retire prematurely in 1987 when the Italian public approved a moratorium on nuclear power, and one in Japan, which retired in 1998.

In non-Anglophone countries, the typical history entails zero cross-sectional variation in regulatory status. Most reactors begin their lives as the property of a single vertically integrated, government-owned utility. After restructuring, an unbundled state-owned enterprise operates all the reactors in competitive wholesale electricity markets. Below, I discuss noteworthy exceptions.

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[5] There are no NPPs in Northern Ireland.

[6] These should not be confused with the *water-cooled*, graphite-moderated reactors of the Soviet Union.

In Japan, all reactors were built, owned, and operated by privately-owned, vertically integrated utilities.[7] A competitive, independently-managed wholesale electricity market was established in 2005 but all utilities remain vertically integrated. Japan is noteworthy in itself as it has built nearly 10% of all reactors globally, almost all of which are based on designs imported from the United States.

Unbundling was always a feature of the nuclear power sector in Argentina, India, Pakistan, and China. Nuclear power plants in these countries were originally owned and operated by government agencies specifically dedicated to all things nuclear, including not only the construction and operation of nuclear power plants, but also nuclear weapons program, the nuclear fuel cycle, and nuclear medicine. These arrangements persist in India and Pakistan but are no longer in effect in Argentina and China.[8]

Several of the 38 countries in the sample enter and exit the panel at various times rather than being represented throughout the period of data availability (1970 to 2017). This largely a consequence of the collapse of communist governments in Eastern Europe after the fall of the Berlin Wall. The electricity market structure of predecessor nations and successor nations were researched and compared to determine if any discontinuity in industry structured occurred at the same time as regime change. In general, all reactors in post-communist countries continued under a similar industry structure in the immediate aftermath of regime change.

While regime change was not found to predict or determine restructuring, the directives of the European Union have clearly been a major driver of restructuring in several European nations. I group European countries into three groups: (1) "early adopters" of restructuring, (2) "reluctant adopters" and (3) EU accession nations. The early adopters consist of the

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[7] Excepting a few tiny demonstration plants and experimental reactors, which were built and operated by the Japan Atomic Energy Agency.

[8] In China, peaceful uses of the atom were separated from weapons development with the creation of state-owned enterprises solely focused on designing, building and operating NPPs. Argentina renounced its nuclear weapon ambitions after its military dictatorship ended in 1983.

United Kingdom, Spain, Sweden, and Finland, which adopted a restructuring regime more comprehensive than required by the EU and/or well in advance of EU deadlines. Reluctant adopters are defined as France, Belgium, the Netherlands, and Germany, typically only complying with the bare minimum required and no sooner than the deadline set by the EU. Switzerland, while not an EU member and therefore not subject to EU regulations, chose to comply with EU rules in order to be able to participate in its neighbors' electricity markets. I classify it as also a "reluctant adopter" because it adopted wholesale competition and unbundling years after those were required by the EU. The final category of European nations consists of those which undertook electricity market liberalization in order to satisfy the requirements for accession to the EU. Among those with nuclear power plants are Slovenia, Czechia, Slovakia, Hungary, Lithuania, Romania, and Bulgaria, which collectively account for 28 reactors. In these cases, the argument for the exogeneity of restructuring is clearest: the desire to join the EU likely overrode any domestic political preferences (and industry lobbying) concerning the structure of the electricity sector.

Globally, among nuclear power plants, ownership unbundling is found predominantly in the United States and the United Kingdom. While ownership unbundling of other types power plants is fairly common in other jurisdictions, my research has found it is very rare for nuclear power plants. When state-owned plants are unbundled, they nearly always remain state-owned and therefore do not change ownership. When investor-owned plants are unbundled, they tend to remain under the corporate umbrella of their former vertically-integrated utility, particularly in continental Europe. Only the occasional acquisition or merger gives rise to ownership unbundling of NPPs in jurisdictions outside of the US and UK. Therefore, because ownership unbundling is quite rare and leasing is only observed at a single plant, for the purposes of the current analysis, I code all plants which are legally unbundled, ownership unbundled, or leased as simply `unbundled`.

2.4 Data

As with all chapters of this dissertation, I rely on the global database of nuclear power plants presented in Appendix A. Below, I discuss the variables of particular relevance to the present chapter.

2.4.1 Measures of Reliability

I select as my dependent variables two measures of reliability, the energy availability factor (EAF) and the unplanned capability loss factor (UCL). Following the PRIS codebook (IAEA, 2005), they are defined as follows:

$$\text{EAF} = \frac{\text{energy generated} + \text{energy available but not supplied}}{\text{reference energy generation}}$$

$$\text{UCL} = \frac{\text{unplanned energy losses}}{\text{reference energy generation}}$$

Reference energy generation is the theoretical maximum that could be produced assuming the plant operated under full power for the entire period. Energy available but not supplied refers to the potential energy that the plant could have generated if the grid operator had called on it to operate for longer and/or at a high power level. Unplanned energy losses refers to energy not generated due on-site conditions attributable to plant management, such as an equipment failure. UCL is not identically equal to $100\% - \text{EAF}$ because it does not include energy unavailable for reasons outside of the control of plant management in the numerator.

Although capacity factor is a direct measurement of output, I do not evaluate it because it is co-determined by demand. In most countries, the effect of demand on the capacity factors of NPPs is trivial, as nuclear power constitutes a small enough fraction of the total supply that it always operates in a baseload condition. However, this is notably not the case in France, where 71.7% of all electric generation was derived from nuclear power in 2018;

Country	**CF (%)**	**EAF (%)**	**UCL (%)**	**N**
Finland	92.4	92.1	1.7	4
United States	90.7	90.8	1.9	105
Spain	86.4	86.4	3.0	8
China	84.8	89.0	0.9	43
World Average[10]	**81.7**	**82.9**	**4.6**	**496**
Russia	81.6	81.0	2.7	38
South Korea	80.1	80.8	1.5	25
Canada	79.8	80.4	5.3	20
Germany	79.5	83.0	7.0	17
United Kingdom	74.9	74.6	13.3	19
France	73.0	75.4	8.9	59

Table 2.1: Output and Reliability of NPPs in Select countries, 2009-2018

other countries with high nuclear shares include Slovakia (55%) and Hungary (51%).[9] In Germany, despite its relatively low and declining share of electricity from nuclear power, NPPs are frequently called on to perform load-following operations to accommodate intermittent renewable energy (Lokhov, 2011). Therefore, I have chosen to analyze reliability rather than output *per se*, because reliability is a necessary precondition to output that is not co-determined by demand or competition from sources of generation with lower marginal costs.

Unlike Davis and Wolfram (2012), I do not hold reference energy generation constant over time; it instead evolves as the reactor's capacity is uprated or downrated. I do this for two reasons. First, the reliability data provided by IAEA have do not hold reference energy generation constant over time. To mirror the method of Davis and Wolfram (2012), it would be necessary to acquire the history of uprates and downrates for the global population of nuclear reactors. Such data, if they exist, were not made available to me by IAEA. Second, the treatment effect estimated by Davis and Wolfram (2012) was predominantly driven by

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[9] Source: PRIS. `https://pris.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=FR`

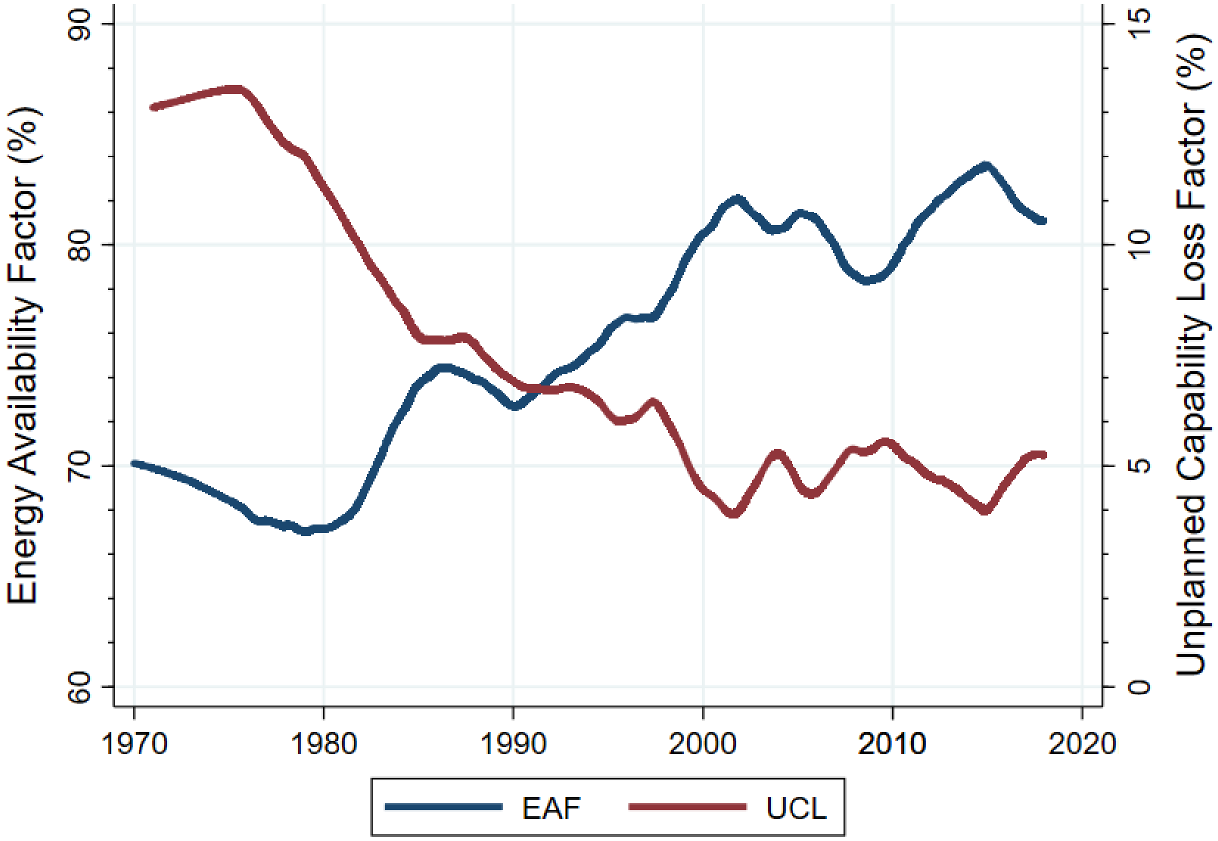

Figure 2.1: Global Trends in NPP Reliability

improvements in reliability, and only secondarily by uprates.

Recent summary statistics for capacity factor, energy availability factor, and unplanned capability loss factor for several countries of interest are presented in Table 2.1. Figure 2.1 displays the global trends in EAF and UCL since 1970. Both the table and figure exclude trimmed data (see Section 2.4.3 below for an explanation).

The industry-wide improvements in reliability cannot be simply explained by the entry of improved designs of NPPs into the market, exit of poorly performing plants, or a increased representation of high-reliability countries in the population of operational NPPs. Table 2.2 reports regressions which establish that reliability has been trending upwards, even when controlling changes in the composition of countries and reactor designs represented in the global population over time. Improvements in reliability of existing plants are clearly part of the reason for the trend; the estimated coefficient in Column (4) implies a cumulative improvement in EAF of 13.5 percentage points from 1970 to 2017.

Dependent Variable: EAF

	(1)	(2)	(3)	(4)
Current Year of Operation	**0.288** (0.044)	**0.288** (0.044)	**0.288** (0.044)	**0.285** (0.045)
Year Construction Began	**0.313** (0.090)	**0.297** (0.096)	**0.377** (0.112)	
Reactor Type Fixed Effects		✓		
Reactor Model Fixed Effects			✓	
Reactor Fixed Effects				✓
Calendar Month Fixed Effects	✓	✓	✓	✓
Country Fixed Effects	✓	✓	✓	
N	592	592	592	592

Marginal effects in **bold**. (Standard errors in parentheses.)

Table 2.2: Secular Improvement in NPP Reliability

2.4.2 Treatment Variables

Figure 2.2 displays the evolution of the mean for each of the three policy treatment variables in the global population of operational NPPs from year 1971 to 2017, inclusive.

Unbundling is present from the earliest years of the sample due to a handful of countries in which nuclear power pants were owned and operated by national atomic energy commissions. The share of unbundled reactors falls during the 1970s and early 1980s as more utility-owned reactors come online. The trend then begins to reverse in the late 1980s, starting with the reorganization of the Soviet nuclear sector after the Chermobyl disaster in 1986. Unbundling disseminated most rapidly in Europe and North America from the late 1990s to around 2010.

Wholesale competition (as faced by nuclear power plants) first appears in 1990, in the United

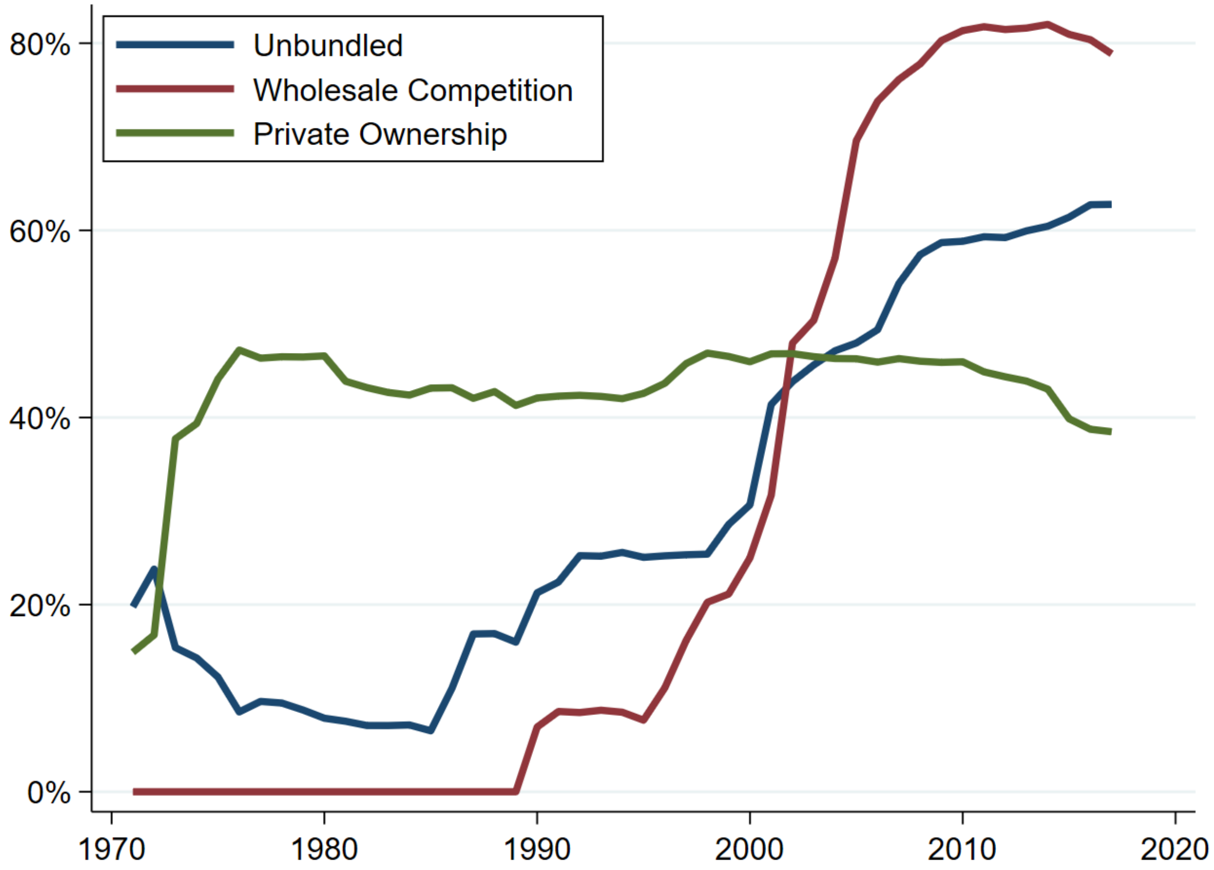

Figure 2.2: Global Trends in Electricity Sector Restructuring of Operational NPPs

Kingdom. Compared to unbundling, this policy disseminates more rapidly and widely, reaching approximately 80% of operational reactors by 2010.

While the earliest reactors were predominantly publicly owned, private ownership of NPPs has hovered between 40% and 50% of reactors since the 1970s, although recently public ownership has tended to increase. While the only cases of change in the type ownership of existing reactors are privatizations, the trend line fluctuates in large part due to the changing composition of the global population. Since the year 2000, most newly built reactors have been publicly owned (whether by utilities or state-owned enterprises), while retirements have been predominantly among privately-owned reactors.

2.4.3 Data Trimming

I trim the data in two major ways before proceeding with the analysis.

First, I drop all 21 reactors classified as the type "other," per the definition in Appendix A.2. These other types of reactors primiarily small pilot experiments. A few of them are quite large and were intended to generate electricity commercially, but so far plants of their design have not yet been replicated to a meaningful extent. This makes them unsuitable for comparison with similar reactors, as each reactor is essentially one-of-a-kind. Furthermore, reactors of these types tend to be more unreliable than the other types, either due to their purpose as experiments or due to inherent design flaws that caused them not to be selected for commercialization.

Second, I trim all data from Japanese reactors as of March 2011 or after. The Great Tohoku Earthquake occurred on March 11th, 2011, precipitating the tsunami that caused the meltdowns at the Fukushima Daiichi Nuclear Power Plant. Since that time, the government of Japan has suspended operations at nearly all its other nuclear power plants, pending regulatory and political determinations of whether they may resume operations. As of August 2019, only nine are currently operating, out of 59 ever built and operated (WNA, n.d.). So long as the remainder are held in limbo—not retired and not yet permitted to resume operation—IAEA records their EAF as 0%. Given that the cause of their inability to operate is neither technical nor economic in nature, I conclude that my model is ill-suited to account for their apparent "low reliability." Fortunately, the actual cause is self-evident and does not require complex statistical analysis to identify. In the interests of improving the precision of the model, I therefore omit all Japanese reactors from March 2011 onward, including those that have been permitted to restart, to avoid any possible selection bias.

2.5 Methods

2.5.1 Fixed Effects

I begin with the two-way, fixed-effects strategy of Davis and Wolfram (2012). However, I depart from them in a several notable ways. Whereas they control for month-of-sample fixed effects, I control for calendar month fixed effects and year fixed effects separately. I argue that year fixed effects should be sufficient to capture macroeconomic shocks and long-term, industry-wide trends in NPP reliability. I include calendar month fixed effects to account for seasonality, which is the first-order explanation for month-to-month variation in NPP operations. Nuclear power plants tend to schedule their refueling and maintenance outages during months of low electricity demand. For most countries, this is the spring and the fall, when the weather is mildest.

In pursuit of even more precise estimation of seasonal patterns, I tested month-by-climate fixed effects in preliminary regressions involving no treatment variables. I matched each plant by latitude and longintude to Köppen climate classification data from Chen and Chen (2013). The Köppen climate classification system consists of 31 unique climates, of which 17 appear in the data once matched with nuclear power plants. To avoid overfitting, I collapsed the climate classifications to the top 5 groups defined by their first letter.[11]

However, this specification was ultimately rejected. This more complex model offers only trivial improvement in within-R^2, 0.025 as compared to 0.024. In other words, climate-by-month fixed effects only marginally improve estimation of within-reactor (i.e temporal) variation in reliability while soaking-up a large amount of the between-reactor (i.e. cross-sectional) variation in reliability, submerging them in unexplained fixed-effects. Graphical inspection of the separately estimated seasonal patterns for each climate group revealed that

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[11] A: tropical; B: desert; C: temperate, D: continental; E: polar.

the seasonality of nuclear power plant operation in deserts, tropical regions, tundra, and even the Southern Hemisphere (for which I included a separate set of month fixed effects) do not vary too greatly from the seasonality typical of plants in temperate regions of the northern hemisphere, where the majority of nuclear power plants have been built.

Davis and Wolfram (2012) rely on reactor fixed effects to control for unobserved, time-invariant characteristics of each reactor that could affect reliability. Given the large number of time-invariant characteristics I observe with my dataset, I investigated the possibility of estimation by random effects. I preformed Durbin-Wu-Hausman test (Nakamura and Nakamura, 1981) and the procedure originated by Mundlak (1978). Both tests concluded that a fixed effects model should be preferred.

2.5.2 Other Controls

Davis and Wolfram (2012) control for a cubic polynomial of reactor age. With reactor fixed effects, the coefficients on reactor age can be intepreted as the effect of reactor aging. With time fixed effects, the coefficients on reactor age can be interpreted as the differences between cohorts of reactors that began operation in different year. In the presence of both fixed effects, the linear term in the polynomial is necessarily collinear with the fixed effects and dropped from the estimation procedure. Furthermore, the interpretation on the remaining quadratic and cubic terms is unclear; therefore, I exclude reactor age from all regressions.

I introduce several additional controls not found in Davis and Wolfram (2012). First, I control for the natural log of GDP per capita in the current year (see Appendix A.3. This is intended to capture any possible effect of differential trends in economic development on the reliability of a country's NPP operations. Next, I control for lags in the dependent variable. In exploratory regressions, I encountered a tremendous degree of serial correlation. I include the first four lags, as the fifth and subsuquent lags are trivial in magnitude and statistically insignificant. Furthermore, I include an additional lag in the dependent variable whose length is contingent on the duration of refuelling schedule. So, for example, if a reactor refuels every eighteen months, then I include an eight-month lag for that reactor. The most common lengths of refueling cycle are twelve, eighteen, and twenty-four months.

2.5.3 Threats to Causal Identification

The primary empirical challenge to estimating the casual effect of electricity market restructuring is non-random assignment of the policy. For the United States, Davis and Wolfram (2012) argue "that the best predictors [of deregulation] are liberal politics and high electricity prices." However, they do not empirically test this relationship. I provide such a test in Table 2.3, which reports the results of a logistic regression of a reactor's exposure to restructuring policies on various predictors.

In unpublished work, I find that liberal politics are strongly positively related with economic outcomes in NPP construction in the United States, specifically overnight capital cost and lead time. Because of the capital intensity of nuclear power plants, their budget overruns and schedule delays can dramatically grow the ratebase of vertically-integrated utilities which regulated on cost-of-service principles. A larger ratebase without proportionately higher demand results in higher electricity prices for consumers. As argued by Borenstein and Bushnell (2000), one of the principal motivations for electricity market restructuring in the United States was the desire to reallocate sunk costs—including, but not limited to, nuclear power plant construction costs—from consumers to utility shareholders by switching from average-cost to marginal-cost pricing.

I find no relationship between a reactor's reliability prior to FERC Order 888—the federal rulemaking that set the stage for electricity sector restructuring in the United States—and a reactor's exposure to restructuring policies. This provides confidence that the causal

Policy Outcome	(1) Divestiture	(2) Divestiture	(3) Wholesale Competition	(4) Wholesale Competition
Publicly-Owned Utility	**0.40**	**0.62**	**0.15**	**0.39**
= 1 if publicly-owned	(-1.03)	(-0.49)	(-1.59)	(-0.62)
State Policy Liberalism	**3.01**	**3.11**	**7.62**	**9.37**
one S.D. increase as of 1996	(2.90)	(2.64)	(5.18)	(4.77)
Construction Lead Time	**6.48**	**5.16**	**3.67**	**1.84**
ln(months)	(2.20)	(1.50)	(1.75)	(0.48)
Overnight Capital Cost	**0.66**	**0.92**	**0.97**	**1.55**
ln($/kW)	(-0.95)	(-0.16)	(-0.056)	(0.65)
average EAF prior to		**1.01**		**1.03**
FERC Order 888 (1996)		(0.31)		(1.05)
N	131	119	131	119

Odds ratios in **bold**. (*t*-statistics in parentheses.)

Table 2.3: Predictors of Electricity Sector Restructuring in the United States

interpretation of the results of Davis and Wolfram (2012) are not undermined by endogenous selection into treatment.

In Europe, a leading driver of the adoption of electricity restructuring policies was a series of directives of the European Union. Directives are policies which require EU member states to achieve a policy outcome while providing flexibility in implementation. These began with directive 96/92/EC in 1996, which began the process of cross-national grid integration and established the first, albeit minimal, rules to promote fair access for third-parties to the transmission grid. This was followed up by 2003/54/EC, according to which all EU members were obliged to legally unbundle their transmission and distribution systems by July 1st, 2004, if they had not already done so. With 2009/72/EC, the unbundling requirements were ratcheted up to require either ownership unbundling or management of the grid by an independent entity. As discussed in Section 2.3.2, several EU members were in compliance with these regulations well in advance of their promulgation. Others were obliged to liberalize as a consequence of the policies. This suggests the possibility of unobserved differences between the early-adopter and the reluctant compilers which could effect both the timing of their policy reforms and their electricity sectors. Therefore, in Europe, I instrument for the adoption of unbundling using an indicator variable that takes on the value 1 in all months including and after the later of either EU accession or July 2004, or 0 otherwise.[12]

This instrument for Europe offers relatively little within-Europe variation in the treatment, as several Eastern European nations acceded to the EU on May 1st, 2004 and two acceded on January 1st, 2007. The only European nations with nuclear power plants outside the EU[13] are Switzerland ($n = 5$), Ukraine ($n = 15$), and Russia ($n = 32$).[14] While Ukraine and Russia would seem to represent a promising control group against which to compare Eastern European nations that acceded to the EU (especially in light of the fact that many of them operate reactors of Soviet design), these two countries did in fact adopt electricity liberalization voluntarily.

However, more institutional history can be exploited to instrument for the industrial organization of nuclear power in the Soviet Union and its successor states. In July of 1986, two months after the Chernobyl disaster, ownership and operation of the nuclear power plants of the Soviet Union were transferred from the Ministry of Energy (MinEnergo), which was responsible for the state-owned, vertically-integrated electric utility, to the newly created Ministry of Atomic Energy (MinAtom). I classify this in my dataset as a legal unbundling. This arrangement (unbundling with continued state ownership) persists to the present day for all nuclear power plants the former Soviet Union and was not interrupted or modified as a result of regime change. The Chernobyl disaster did not trigger unbundling or other administrative reforms in fellow Warsaw Pact nations, perhaps in part because the RBMK

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[12] Naturally, this variable always takes on the value zero in all countries which have never acceded to the EU.

[13] The United Kingdom exited the European Union outside of the sample period.

[14] Reactors operational as of 2017.

design at Chernobyl was never exported outside of the Soviet Union.[15] Thus, unbundling can be instrumented for in Russia, Ukraine, Latvia, Armenia, and Kazakhstan. However, the introduction of competitive electricity markets remains potentially endogenous.

Ultimately, because I find statistically null or empirically negligible results in most of Europe when estimating the model by OLS, I do not present the result of the instrumental variables strategy herein. The IV estimates are less precise and return qualitatively similar conclusions. The foregoing discussion was included for the interest of future researchers who may wish to investigate this matter further.

2.5.4 Standard Errors

the prevailing econometric wisdom is that standard errors should be clustered at the level of the treatment assignment. In the context of the United States, the restructuring was determined by state policy but the impact was not necessarily homogeneous within states. In particular, publicly-owned NPPs were generally exempt from restructuring policies (although some chose to divest their NPPs anyways) and the reactors at Diablo Canyon, San Onofre, and Donald Cook sites were not unbundled despite the adoption of restructuring policies by the states in which they were located. Thus, Davis and Wolfram (2012) report standard errors that are clustered by plant site.

However, outside the United States, restructuring policies (or the lack thereof) is substantially more uniform within jurisdictions. Therefore, given my global sample, I cluster standard errors by the jurisdiction with authority of electricity sector policy. The relevant jurisdictions are states in the United States, provinces in Canada, and country in the rest of the world.

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[15] The RBMK is of a LWGR reactor type. The Soviet Union only exported PWR-type reactors to its allies.

2.6 Results

Table 2.4 reports the results of two regression specifications in which EAF is the outcome of interest and two for UCL. Columns (1) and (3) report results for a relatively parsimonious model, while Columns (2) and (4) report results for the more complex model. Before proceeding to the results, I will guide the reader through interpretation. The coefficients are in terms of percentage points. Note that, when interpreting columns (1) and (2), an increase in EAF represents higher reliability; when interpreting columns (3) and (4), a decrease in UCL represents higher reliability. In the models with lagged dependent variables, the other coefficients must be adjusted to account for the propagation of treatment effects forward in time through the lagged terms to arrive at an estimate of the long-run effect of the treatment.

All four models find statistically insignificant effects of all three electricity sector restructuring policies, unbundling, wholesale competition, and privatization. This is in stark contrast to the findings of Davis and Wolfram (2012) for unbundling in the United States. In Column (2), after adjusting for the lagged dependent variables, the effect size of unbundling is approximately a 2 percentage point increase[16], with a two-sided p-value just below 10%. Irrespective of the marginal statistic significance, the magnitude of effect is quite small and leads to the conclusion that restructuring has had little effect globally.

I investigate possible heterogeneity in treatment effects by repeating the regression of Column (1) in Table 2.4 with interaction terms representing groups of countries with similar histories of electricity sector restructuring (or lack thereof). I present the estimated treatment effects in Table 2.5.

The clearest success of restructuring can be found in North America, where the combined effect of unbundling and wholesale competition raised reliability by approximately 14 percentage points. Conversely, unbundling in Europe appears to be associated with worse

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[16] The exact size depends on which refueling schedule lag term is included.

Dependent Variable	(1) EAF	(2) EAF	(3) UCL	(4) UCL
GDP per capita	**21.5**	**3.7**	**-4.6**	**-0.7**
$ln(GDPpc_{c,y})$	(3.12)	(1.49)	(-1.65)	(-1.00)
Unbundled	**1.0**	**1.5**	**-0.6**	**-0.3**
= 1 if unbundled	(0.36)	(1.64)	(-0.49)	(-0.69)
Wholesale Competition	**0.1**	**-0.2**	**-0.6**	**-0.2**
= 1 if wholesale competition exists	(0.037)	(-0.51)	(-0.62)	(-0.63)
Private Ownership	**3.0**	**0.3**	**2.6**	**-0.2**
= 1 if private ownership > 50%	(1.20)	(0.19)	(0.88)	(-0.12)
Serial Correlation				
One-Month Lag		**0.69**		**0.58**
Y_{t-1}		(15.0)		(20.7)
Two-Month Lag		**-0.18**		**0.01**
Y_{t-1}		(-7.66)		(0.81)
Three-Month Lag		**0.06**		**0.06**
Y_{t-1}		(11.6)		(6.88)
Four-Month Lag		**-0.02**		**0.04**
Y_{t-1}		(-3.87)		(5.20)
Peer Effects				
Contemporaneous Effect		**0.11**		**0.13**
$\bar{Y}_y$ *of same-family reactors*		(4.35)		(2.87)
Five-Year Lag		**0.07**		**-0.00**
$\bar{Y}_{y-5}$ *of same-family reactors*		(1.75)		(-0.25)
Other Controls				
Refuelling Schedule Lag		✓		✓
Year Fixed Effects	✓	✓	✓	✓
Calendar Month Fixed Effects	✓	✓	✓	✓
Reactor Fixed Effects	✓	✓	✓	✓
N	183,497	89,559	180,328	94,285

Marginal effects in **bold**. (t-statistics in parentheses.)

Table 2.4: Impact of Electricity Sector Restructuring on NPP Reliability

reliability. In the case of ex-Soviet countries, this may be explained by the regulatory responses following the Chernobyl disaster and/or the political and economic destabilization resulting from the fall of communism.

In an unreported regression, I investigate restructuring in Canada separately from the United States by restricting the sample to PHWRs. Under this specification, the point estimates suggest that the reliablity of reactors in Ontario benefited strongly from the introduction of wholesale competition in 2002 while suffering from unbundling in 1999, with an overall positive net effect. The leasing of Bruce NPP to a private enterprise is estimated to have increased output modestly on top of the other two reforms. However, these policy changes coincide with an era when many reactors in Ontario were mothballed for technical reasons that predate restructuring. The point estimates are statistically noisy and the signs may be misleading, which is why I do not report them here. Further research would be needed to clear up the identification. For now, I conclude qualitatively that restructuring in Ontario appears to have been a success of similar magnitude to that seen in the United States.

For Western and Northern Europe, the result is quite baffling. Most of these countries imported designs of NPPs from the United States or based their own designs on American intellectual property. As shown in Table 2.4, reactors of the same family are correlated in their reliability, which I interpret as the dissemination of family-specific operating knowledge. I would have expected to see American best practices disseminate to these NPP operators in Europe, especially once they faced sharper incentives to increase output. The only apparent success is with privatizations among early-adopter European countries, namely Britain and Spain, which is estimated to have raised reliability by about four percentage points.

Considering the rest of Table 2.5, I will offer a few final comments in passing. The effect of private ownership cannot be estimated for many regions where no privatizations occurred; if ownership status is time-invariant, the coefficient cannot be estimated under two-way fixed effects. Unbundling appears to have prompted dramatic improvements in reliability in the

Dependent Variable: EAF

Region × **Policy**	**Unbundling**	**Wholesale Competition**	**Privitization**
North America	**6.5**	**7.7**	**-2.6**
USA, CAN	(3.5)	(2.1)	(3.9)
Early-Adopter Europe	**-5.6**	**1.9**	**4.1**
GBR, SWE, FIN, ESP	(1.6)	(1.5)	(1.6)
Reluctant Europe	**-8.5**	**-0.4**	**-9.1**
FRA, BEL, NDL, DEU, CHE	(1.5)	(2.0)	(0.7)
Ex-Communist EU Accession Nations	**-0.1**	**-1.6**	N/A
CZE, SVK, SLV, HUN, ROU, BGR, LTU	(4.3)	(3.4)	
Ex-Soviet Union	**-11.0**	**2.4**	N/A
RUS, UKR, ARM, KAZ	(2.2)	(1.6)	
East Asia	**1.0**	**-8.1**	N/A
CHN, TWN, KOR, JPN	(2.3)	(2.2)	
Global South	**26.6**	**-7.7**	N/A
IND, PAK, IRN, ZAF, ARG, BRA, MEX	(6.9)	(2.6)	

Marginal Effects in **bold**. (Standard errors in parentheses.)

Table 2.5: Heterogenous Treatment Effects of Electricity Restructuring Policies

Global South, an effect which is offset by a reduction attributed to wholesale competition. As with the findings in Canada, I suspect these conflicting signs reflect a certain degree of overfitting.

2.7 Conclusion

I conclude that the success of restructuring the electricity sector has been mixed and uneven globally. The United States, Canada, and the Global South stand out as exhibiting the greatest improvements in NPP reliability in response to restructuring. For Europe and Asia, the effect of restructuring policies have been modest at best, usually statistically insignificant, and in some cases apparently quite negative.

I see two principal avenues for improvement on the current work. The first is the incorporation of the latest methods that correct for the violation of the assumptions of the classical 2×2 difference-in-difference framework under a two-way fixed effects estimation with more than two time periods and variation in treatment timing (Callaway and Sant'Anna, 2020; Goodman-Bacon, 2021). The second is more careful event studies of particular countries to resolve or understand the cases where the signs of coefficients in Table 2.5 point in a direction opposite of that predicted by theory.

Chapter 3

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

3.1 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 state regulators and regulated utilities through public participation 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 typically hold seats on the relevant Congressional committee). Each group provides and receives various benefits from one another, which forms 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 3.3, 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 3.4, 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 3.5, 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.

3.2 Historical Background

3.2.1 Outline of Reactor Licensing

Congress originally entrusted licensing and regulation of civilian nuclear reactors to the Atomic Energy Commission (AEC). The Commission was headed by five commissioners appointed by the President and confirmed by the Senate. These appointments were not at the pleasure of the President; instead, the commissioners serve fixed terms of five years, staggered such that one was replaced annually. The same arrangement was retained for the Nuclear Regulatory Commission (NRC) when it took over the regulatory responsibilities of the AEC in 1975.

Historically, the licensing of nuclear power plants in the United States has occurred according to a two-step process, under the provisions of Title 10, Part 50 of the Code of Federal Regulations (abbreviated 10 CFR 50).[1] A utility seeking to construct a nuclear power plant must first apply for a construction permit (CP). Second, as construction approaches completion, the utility then applies for an operating license (OL), which is required before commercial operation may begin. Most of the minutiae within these steps are not particularly important for the present work.[2] That said, one aspect of the process that merits mention is the role of public hearings:

> *The Atomic Energy Act requires that a public hearing be held before a construction permit is issued for a nuclear power plant. This hearing is conducted by a three-member Atomic Safety and Licensing Board (one lawyer, who acts as chairperson, and two technically qualified persons). Members of the public may submit written*

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[1] A new, one-step process is now available under 10 CFR 52, but this is not relevant to the historical context.

[2] A more detailed written description is provided by NRC (2020). A diagram of the process can be found on page 73 of Cohen (1979).

> *or oral statements to the licensing board to be entered into the hearing record, or they may petition to intervene as full parties in the hearing.*[3]

Public hearings of the AEC and NRC were one of the principal fora in which battles over nuclear power were waged, as will be discussed at length in Section 3.2.2.

3.2.2 Historical Narrative

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.

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).

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[3] Source: NRC (2020)

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"[4] and "the tyranny of scientific priesthood,"[5] espousing instead an ethic of "democratic control of technology."[6] 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 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 they 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 revised its procedures to comply 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).

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

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

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

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).[7] The public hearings were held over the course of the next eighteen months and involved 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

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[7] 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.

(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.[8] 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 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.

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[8] 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).

3.2.3 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 laid the groundwork for 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 in Wellock (1998, p. 3): 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."

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 form of 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 for 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 substantive environmental protection, radiologic hazards from routine operation, and process—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 3.5.

3.3 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 A.5. Below, I describe the variables at a high level and present the data graphically.

3.3.1 The Licensing Hold-Up

In Figure 3.1, 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.[9]

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 notion 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 3.1 to the effect of the court's ruling.

In Figure 3.2, I plot an identical 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). 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 strongly suggests that something beyond EIS paperwork is responsible for the trend.

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[9] For reasons I discuss in Appendix B.4, the estimate of the effect of an unanticipated event could be biased by endogenous selection into treatment when the outcome variable is duration of time. However, in regressions available with the online code appendix, I find that there is negligible bias arising from this issue.

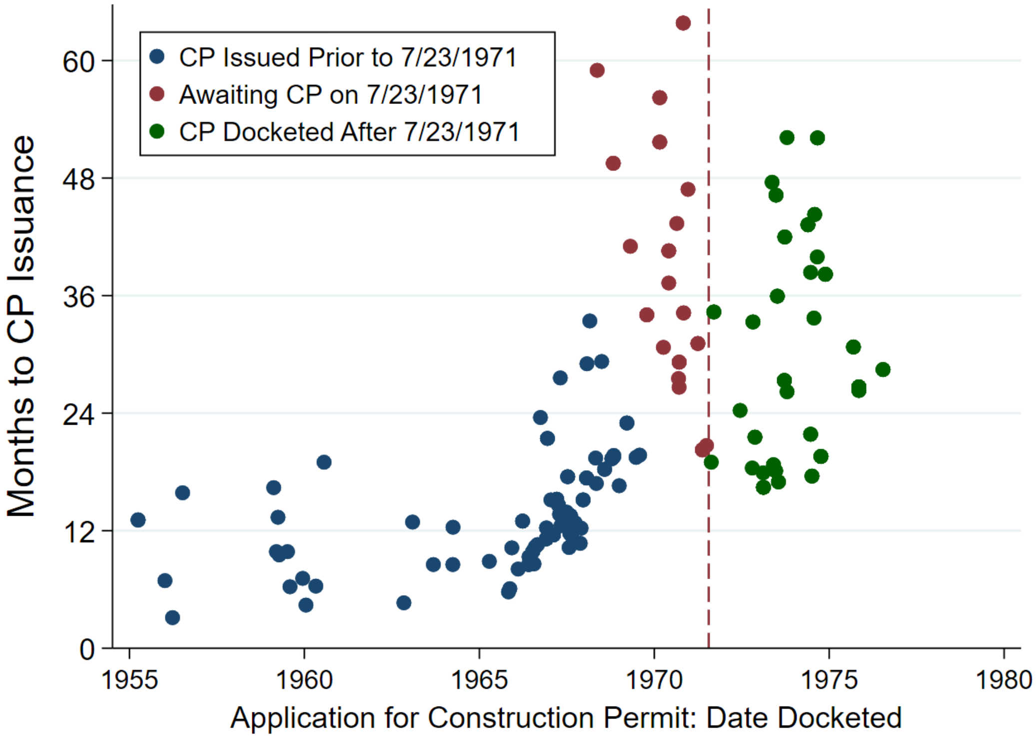


Figure 3.1: Trends in Construction Permitting of U.S. NPPs

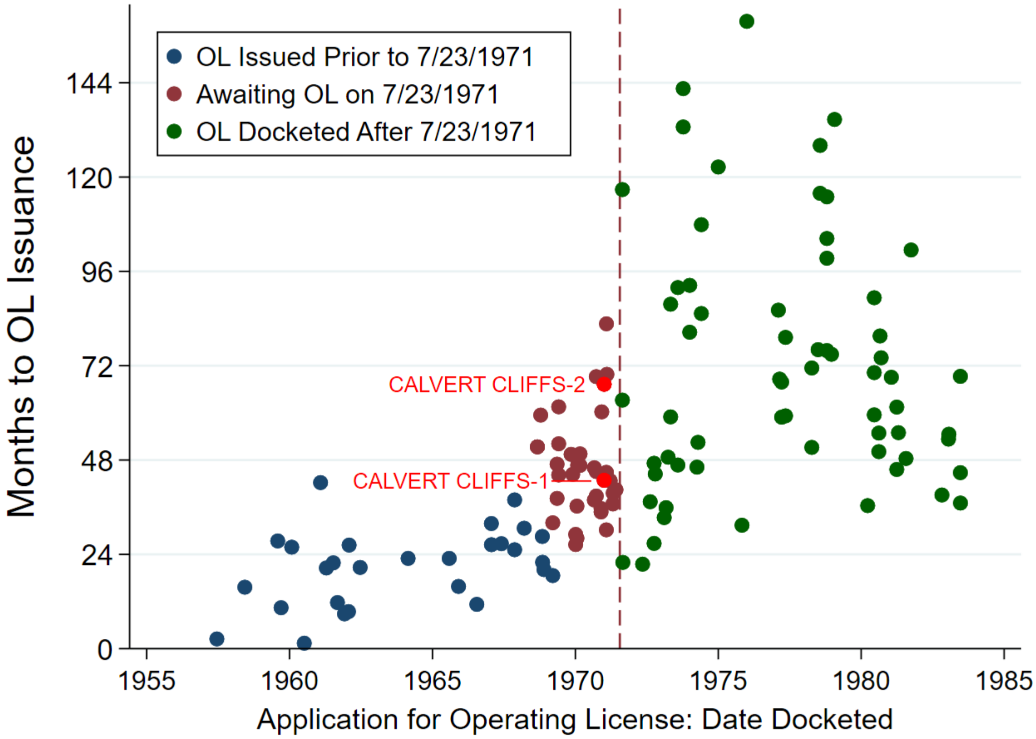


Figure 3.2: Trends in Operational Licensing of U.S. NPPs

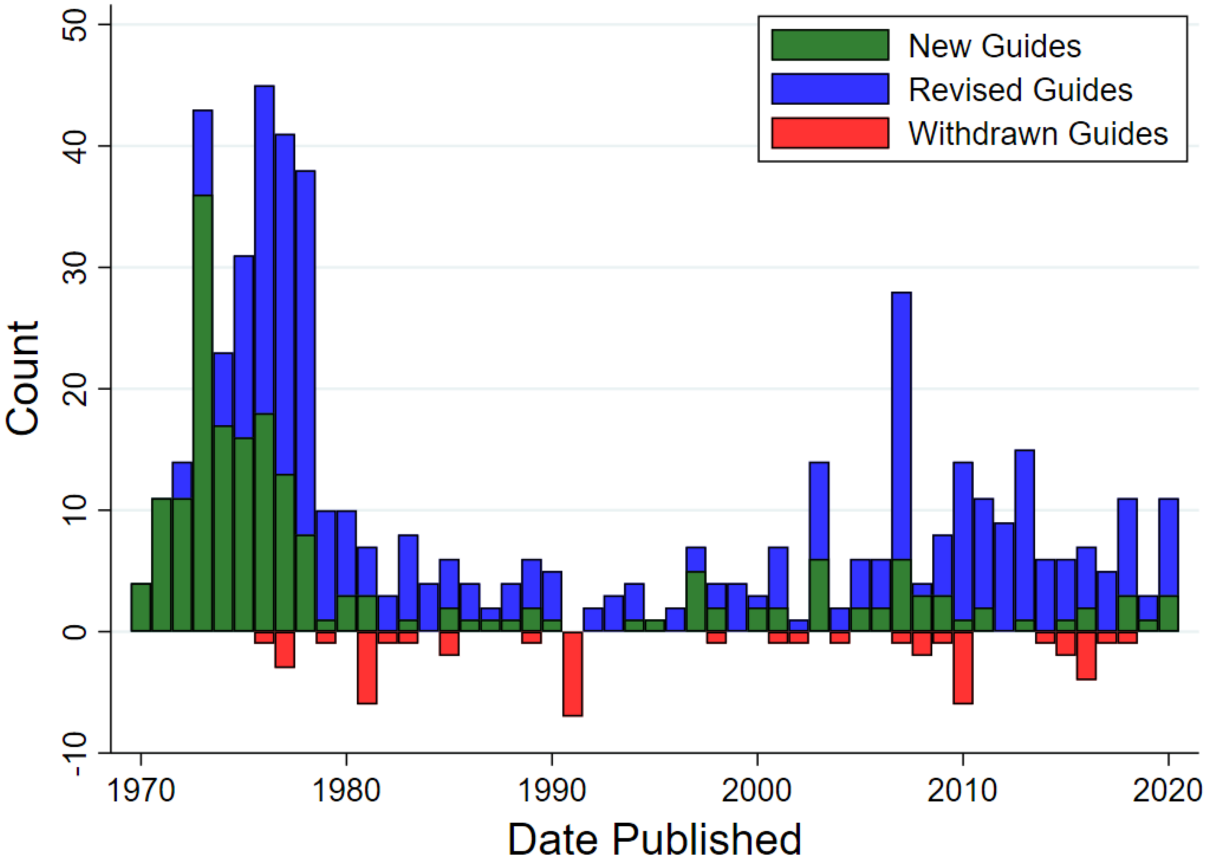


Figure 3.3: Publication of Regulatory Guides Relating to the Design or Construction of Nuclear Power Plants by Year

3.3.2 Turbulent Regulatory Guidance

In Figure 3.3, 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 A.5.1, 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.

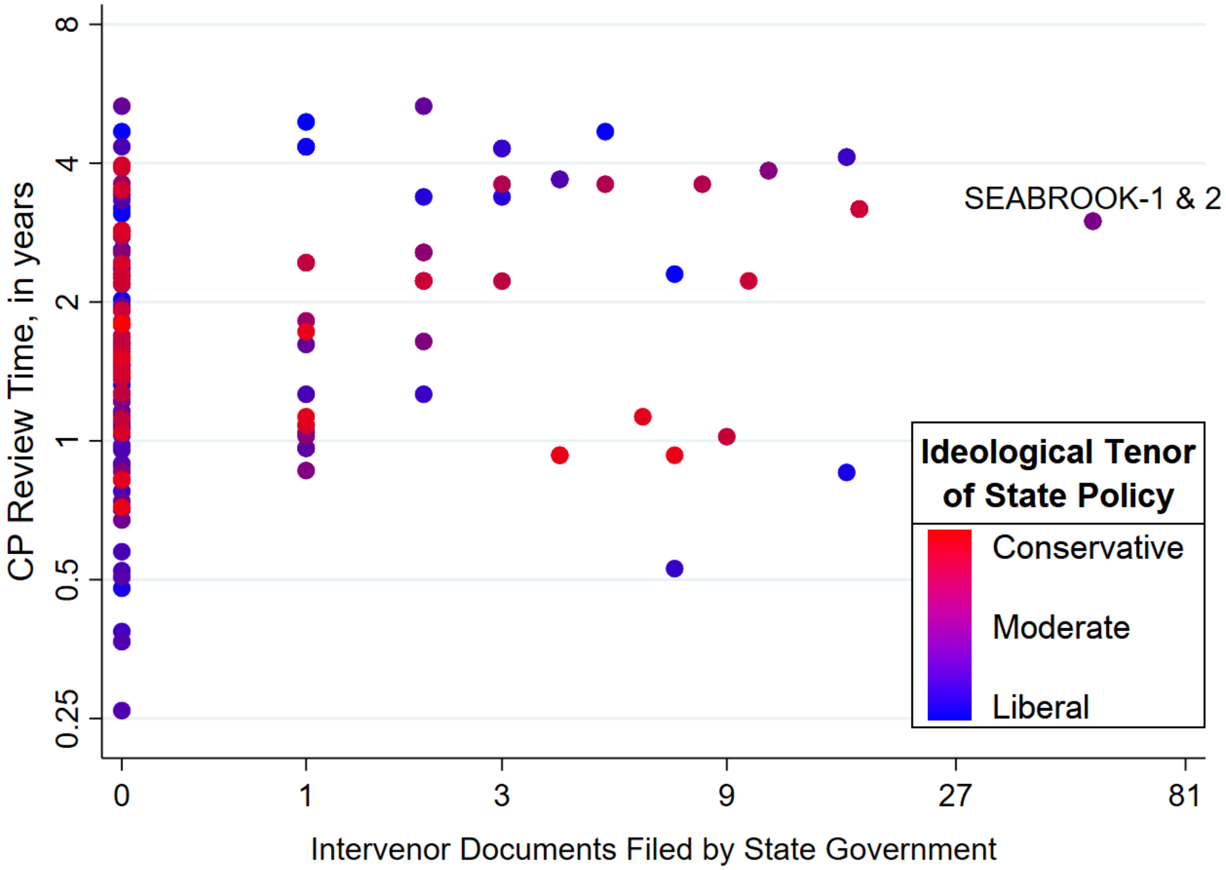
A substantial number of guides were withdrawn in 1981, 1991, and 2010. "Regulatory guides may be withdrawn when they are superseded by the Commission's regulations, when equivalent recommendations have been incorporated in applicable approved codes and standards, or when changes in methods and techniques 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 is that the NRC staff periodically review the existing regulatory guides without any particular impetus, to revise or withdraw them as appropriate.

3.3.3 State Intervention in Licensing

Figure 3.4 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. 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 A.6.

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 3.5.

Figure 3.4: State Participation in CP Proceedings



Overall, the picture provided by Figure 3.4 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 3.5 is equivalent to Figure 3.4 except that it displays data for state participation in the proceedings for operating licenses. Figure 3.5 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,[10] and Diablo Canyon Units 1 & 2.

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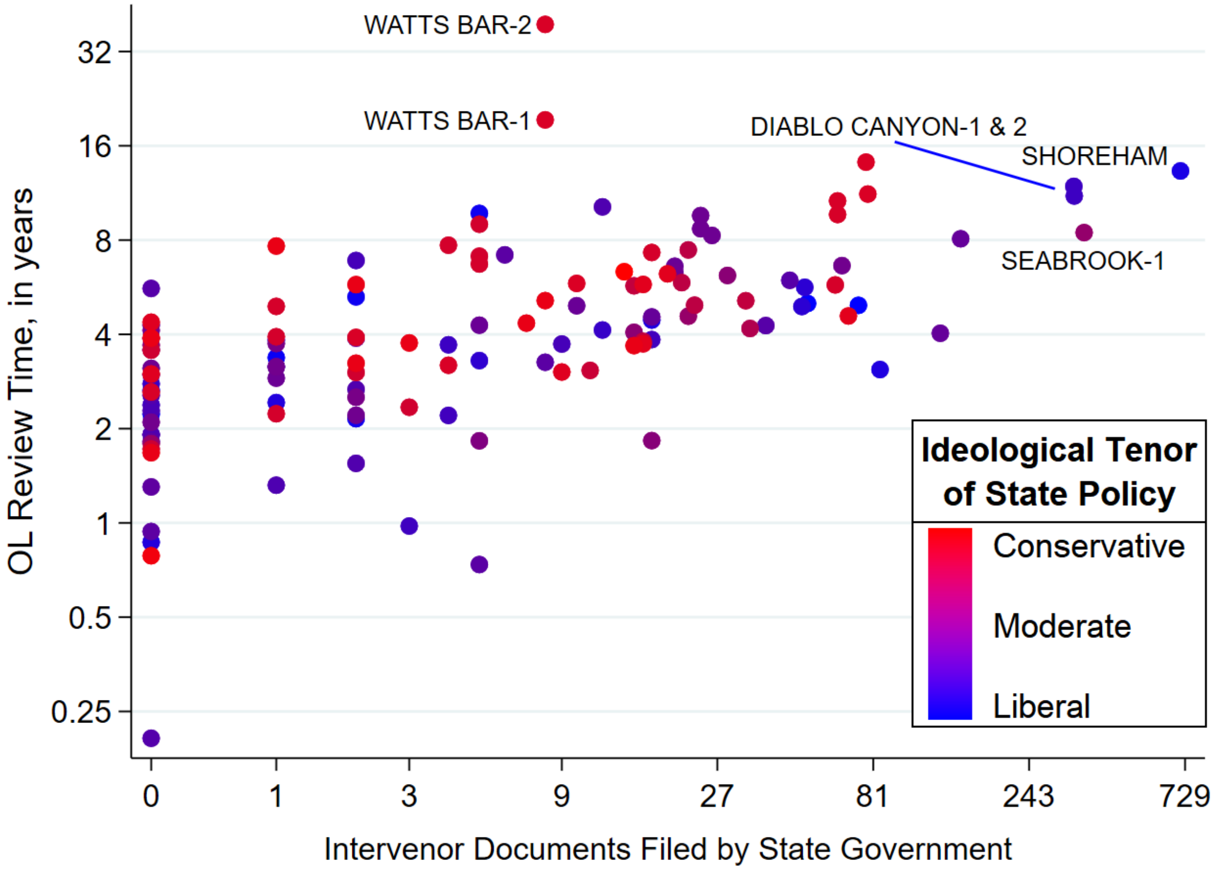
[10] Construction of Seabrook Unit 2 was abandoned for economic reasons. Thus, it never received an OL and cannot be displayed on this graph.

Figure 3.5: State Participation in OL Proceedings



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 3.4 and 3.5, the overall level of state engagement with CP proceedings is much lower than with OL proceedings. The mean number of documents in the 173 CP proceedings that reached a conclusion[11] 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.

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

I also collected equivalent data on county government participation in licensing. The equivalent graphs 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 during the OL proceedings on the grounds that Long Island could not feasibly be evacuated in the event of an emergency.

3.3.4 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 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

Figure 3.6: Amendments to Preliminary Safety Analysis Reports in CP Licensing Cases

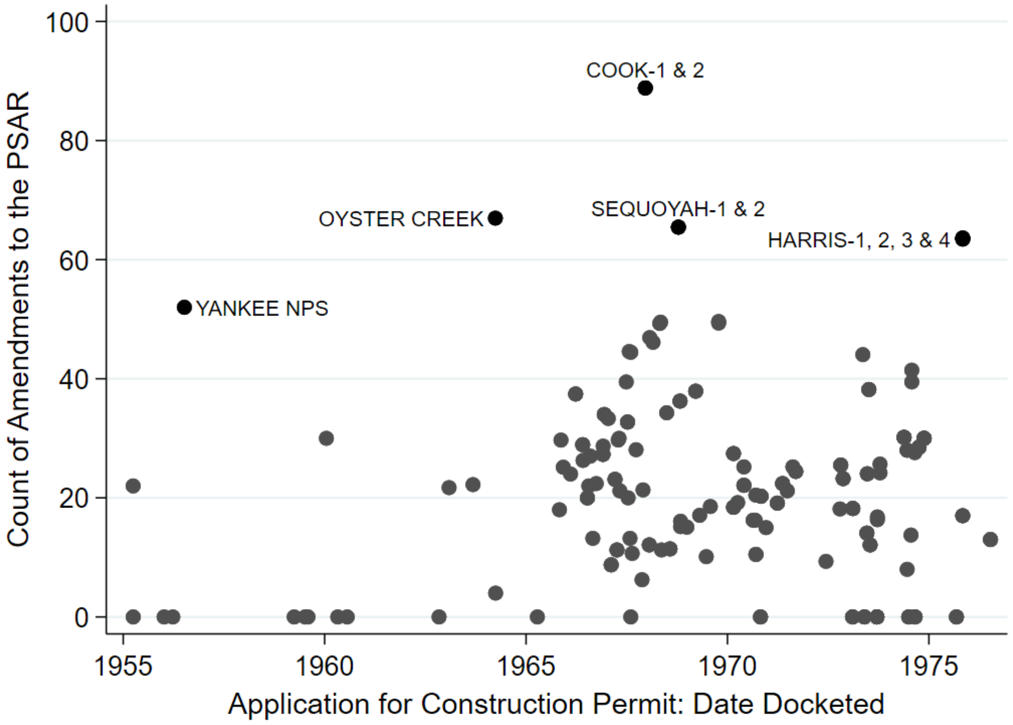
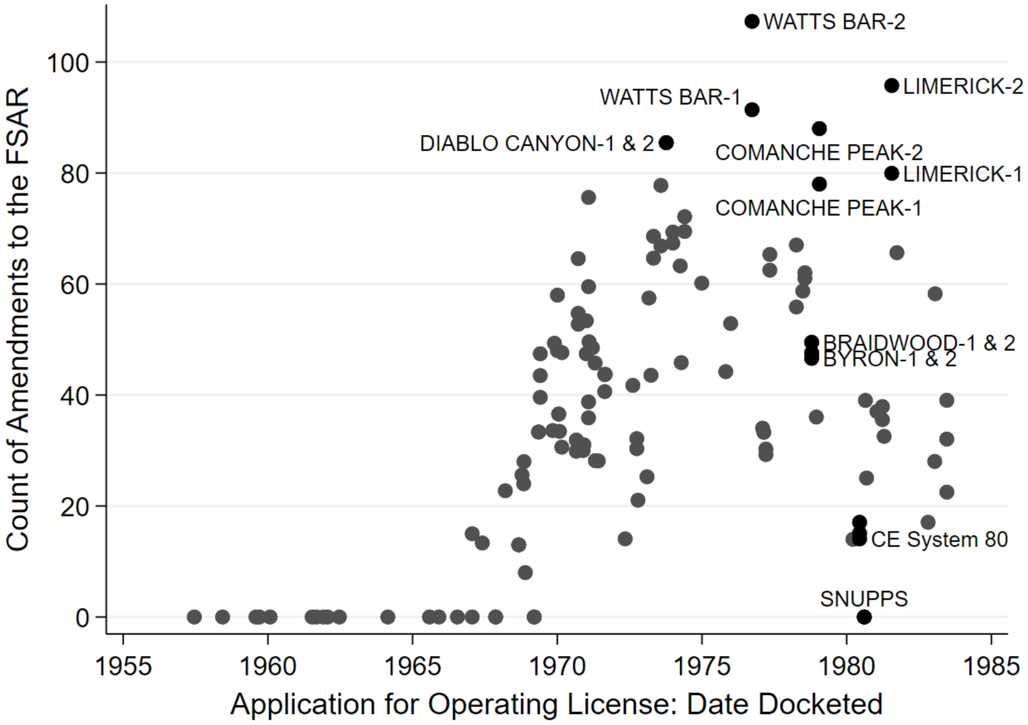


Figure 3.7: Amendments to Final Safety Analysis Reports in OL Licensing Cases



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 3.6 and 3.7 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 the SNUPPS[12] plants (Callway and Wolf Creek),[13] 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). This is mildly supportive of the idea standardization of power plant design streamlined the licensing process, but the sample size is too small to draw any firm conclusions.

3.4 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 3.1 and 3.2. I say “covariates” and not “causes” as causal identification is not achieved with the present methods.

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[12] An acronym for “Standardized Nuclear Unit Power Plant System”

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

3.4.1 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). All dependent variables are log-transformed. Historically in the nuclear industry, delays are much more common than unexpected progress ahead of schedule, so the assumption of symmetrical errors in a linear model is unrealistic. The empirical distributions of the untransformed version of these variables have long right-tails.

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 very likely to be causally related to the licensing hold-up observed in Figures 3.1 and 3.2 but 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 3.3.3.

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; the count of FSAR amendments is excluded for the regression of CP review time, as the FSAR only pertains to operational licensing.

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 longitudinal variable 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-owned utilities, months of construction suspension, and a control for measurement error relating to multi-unit construction, which is described in detail in Appendix A.2.1. Nameplate electric capacity and months of construction enter into the right-hand side of the equation linearly because experience from Chapter 1 indicates that a log-linear functional form has the best fit to the data.

3.4.2 Results

Table 3.1 displays the regression results for the models described in Section 3.4.1. 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 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

Dependent Variable: $ln(Date_1 - Date_0)$

	(1)	(2)	(3)
Date$_\mathbf{1}$	CP Issued	OL Issued	Comm. Op.
Date$_\mathbf{0}$	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.2.3)			(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 3.1: 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 3.2: Reestimating Model (2) of Table 3.1 with Sample Restrictions—Marginal Effect of Covariates of Interest on Time to OL Issuance

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

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 3.2, I evaluate the robustness of the findings regarding state intervenor activity and amendments to the FSAR. I rerun the regression in Model (2)[14] 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.

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[15] 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 fragmentation 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 emergence of nuclear power as an issue of mass controversy, I perform an auxiliary analysis to test whether the nature of state intervenor activity varied over time. In Table 3.3 I evaluate whether a state's politics is associated with the level of that state's participation in the licensing of each reactor. All variables have been standardized for ease of interpretation. All models include fixed effects

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[14] I include the same variables in all cases but only display the coefficients of interest in Table 3.2.

[15] 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.

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 A.6 for sources and definitions), as a robustness check. 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 3.3. 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 across the two 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 can only point to the prior qualitative work of Surrey and Huggett (1976), Joppke (1992), Wellock (1998) to justify that particular claim.

3.5 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 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 1$^{\text{st}}$, 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 A.5.3.

3.5.1 Trends in Licensee Event Reports

Figure 3.8 plots the time trend in the average number of LERs filed per month for operational[16] 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, 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 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 an differences in document survival: older, pre-digital documents should be expected to survive at *lower* rates than more recent, digitized documents.

In Appendix A.5.3, 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.[17]. This change in the regulations occurs after the sharp declines of the late 1990s, and therefore cannot explain it.

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[16] 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.

[17] 65 FR 63787

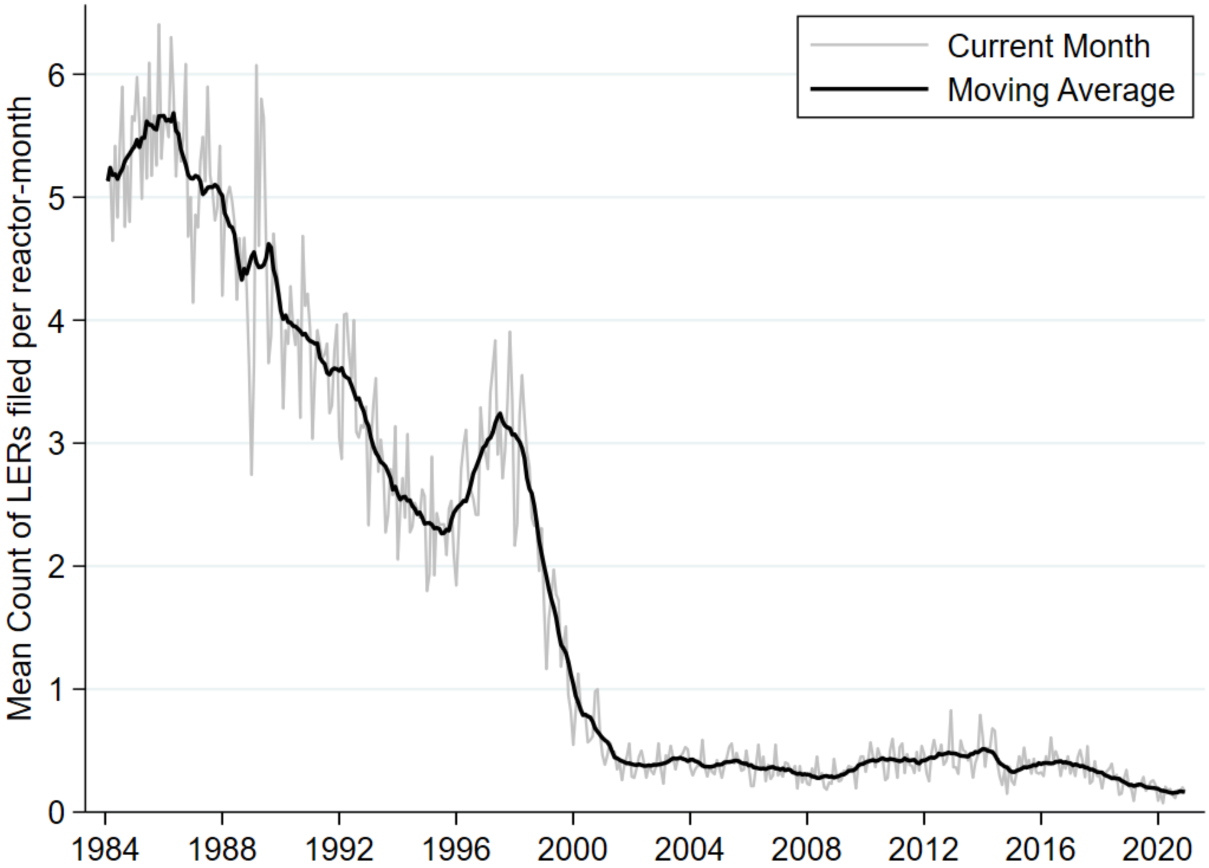

Figure 3.8: Average Rate of LER filing per Reactor

As discussed in Chapter 2 and found in 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 relationship between the unplanned capability loss factor (UCL)—a measure of reliability sourced from IAEA PRIS—and the count of LERs filed. However, the magnitude of the relationship between reliability and LERs is only sufficient to explain approximately a five percentage point reduction in the mean count of LERs filed per reactor per month.

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 in Section 3.5.2, 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 reactors will 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, possibly because of learning or changes 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 by m):

$$ln(E\big[LER_{it}\big]) = \alpha_i + \beta_y + \gamma_m \tag{3.1}$$

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 3.9 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 3.9 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[18] 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[19] filed 9.4% more LERs (standard error: 3.0%), on average,

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

[19] I do not use fixed effects for every possible year of retirement because most years have zero or one reactor

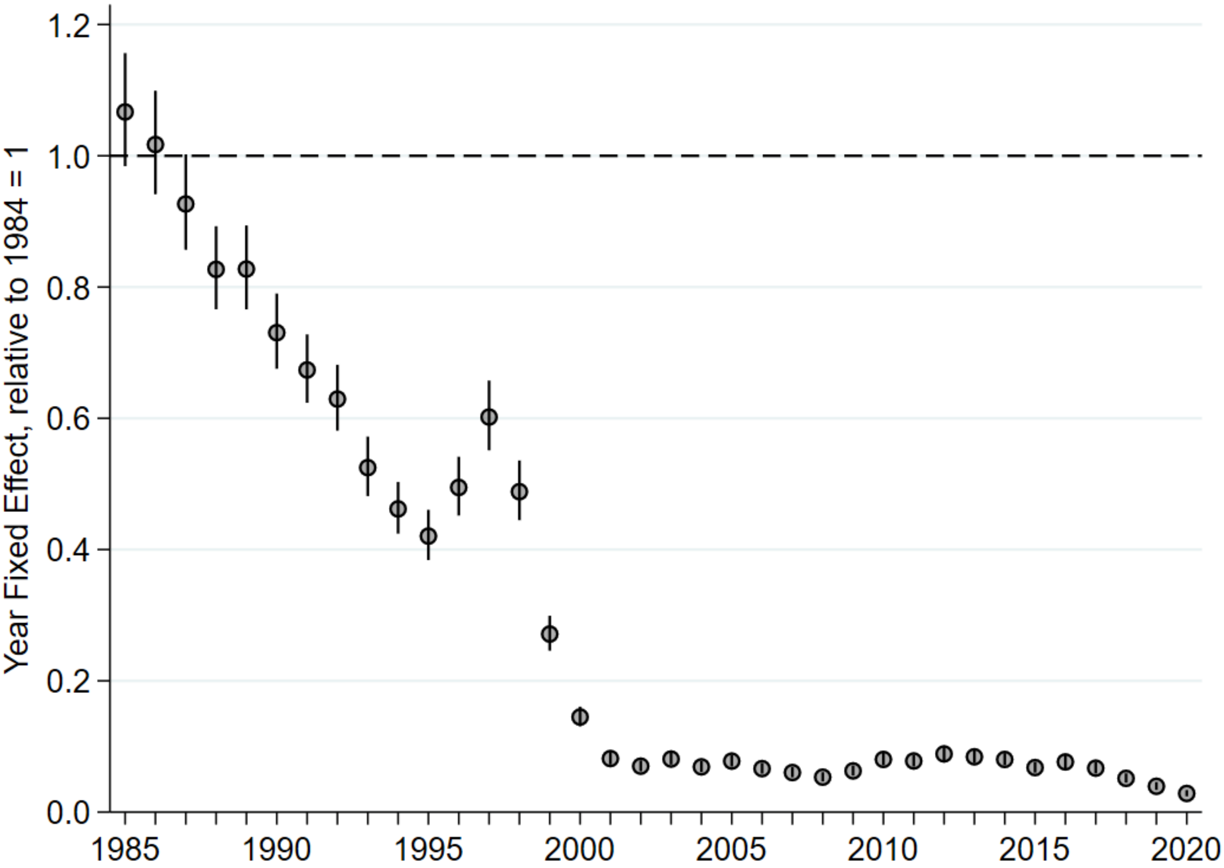

Figure 3.9: Year Fixed Effects Estimated by Eq. 3.1, de-transformed (e^{β_t})

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 related to market exit, but the predominant effect explaining the overall trend in Figure 3.8 is within-reactor improvement over time.

3.5.2 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

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retirements.

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 3.5.1 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.[20] Therefore, I take great care to control for 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.

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

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[20] 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, 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 3.3 have extremely weak joint relevance, well below the conventional threshold of 10 for the F statistics.

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.2.4 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 3.4, 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 one-period 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 contemporary state politics have casual effects on a reactor operational safety separately from any historic impact 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:[21]

> *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 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

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

a state's policy liberalism as a proxy for the ideological antipathy of state policymakers towards nuclear power.

A state policy which I can measure directly is restructuring of the electricity sector. I control for whether the reactor in question has been unbundled from traditional ownership by a vertically-integrated utility.[22] Davis and Wolfram (2012) find that unbundling improves nuclear power plant reliability, a finding which I replicate in Chapter 2. Reliability and safety are surely related.

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.

Given the presence of time fixed effects, the interpretation of the coefficients on reactor age is

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[22] See Chapter 2 for the definition of unbundling and the data sources.

purely cross-sectional in nature–the coefficients tell us how older reactors compare to newer reactors at the same point in time. This is, in effect, equivalent to assigning each plant to "cohorts" based on age, but 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.

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[23]

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

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[23] see Appendix A.2.6 for definitions).

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 similar vintage and greater similarity in design.

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 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.

Treatment Variables

I consider six treatment variables, which are listed and defined in Table 3.4. 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. That is, two plants which proceeded through the licensing process at the same point in time 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 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, 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 licensing and (Y) operational safety at a fixed point in time, 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 3.4: Treatment Variables

3.5.3 The Effect of Licensing Activity on Operational Safety

Table 3.5 displays the results of the Poisson regression described in Section 3.5.2. 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 3.2. 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[24] in license review time and corresponds to a reduction in LERs by 42%.[25]

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 3.6). 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 3.5, 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

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

[25] $3.9^{-.4} = 0.58$—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)
4^{th}-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 3.5: Predictors of Licensee Event Reports

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 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 3.3, 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 3.1 exhibits comparatively less escalation in CP review times than OL review times, which are shown in Figure 3.2. 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 cross-sectional analysis is 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 explanation 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.

Alternate Specification relative to Model (4) in Table 3.5	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 3.6: Robustness of Results to Alternative Specifications

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 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.

Contemporaneous state policy liberalism appears to have a substantial impact on the safety of nuclear power operations; specifically, it is associated with fewer LERs. However, the effect would be better identified in a two-way fixed effects model, which is not appropriate for the current work.

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) and Chapter 2 of this dissertation: merchant generators respond to sharper economic incentives by improving their operations. As with the other panel variables, this effect would be better identified in a two-way fixed effects model.

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 3.5.2 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.

3.6 Conclusion

In this chapter, I have presented archival data quantifying various regulatory phenomena in the licensing of American nuclear power plants in the second half of the 20$^{\text{th}}$ 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.

I exploited 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.

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Appendix A

The Benson Database of Nuclear Power Plants

This appendix documents the compilation of the database upon which I rely for all analyses in this dissertation. The data, excepting any data which is subject to IAEA data-sharing restrictions, has been made available at `https://github.com/a-g-benson/Global-NPP-Database`.

A.1 Preliminaries

A.1.1 Unit of Observation

The unit of observation is the "nuclear generating unit," which is a discrete collection of equipment and structures which are jointly necessary to safely and efficiently generate electricity from nuclear fission. A nuclear power plant may host multiple nuclear generating units, which may be constructed and operated independently.

For brevity and to avoid confusion with other several other uses of the word "unit," I refer instead to “reactor” as a metonym for “nuclear generating unit.” The reactor is a central component of a nuclear generating unit, although it would not be able (or permitted) to function without the other components, such as the reactor coolant system, containment, steam turbine, structures for discharging waste heat, generator, and electrical switchyard.

A.1.2 Types of Data

My database consists of a diverse mix of cross-sectional, time series, and panel data. The primary structure of the database is cross-sectional in nature, recording for each reactor pertinent data about its identity, location, ownership, technical specifications, important dates (of construction, operation, and retirement), and so on. In general, in cases where a variable may take on different values at different points in times (e.g. a reactor’s ownership may change hands), the reactor is assigned a value for that variable which corresponds to the date it began construction.

In certain cases, discussed in the body text or below, time series or panel data may be transformed into a cross-sectional variable by computing the sum or average value of that variable within a range of specified dates appropriate for the reactor, such as the dates on which construction began and finished.

Where the analysis is panel in nature (as in Chapters 2 and 3), the cross-sectional database is merged onto one or more monthly panel datasets.

A.1.3 Sample Definition

The foundation of the database is provided by the Power Reactor Information System (PRIS) of the International Atomic Energy Agency (IAEA). While certain basic information about each NPP is available through a public website[1] and through various IAEA publications (IAEA, 2019), I was granted temporary access to a private version of the PRIS database restricted to authorized users.[2]

The IAEA PRIS database consisted of 1,056 reactors as of the month of access (July 2018). The reactors in this sample consist primarily of the global population of all nuclear reactors which have ever entered operation for the purposes of commercial electricity generation. It furthermore includes all commercial reactors which have begun construction, including those which were never finished and those that are presently under construction. PRIS classifies a reactor as having begun construction if "the first major placing of concrete, usually for the base mat of the reactor building, was carried out" (IAEA, 2005). Construction activities involving site preparation do not qualify.

In addition to all reactors which meet this definition of having begun construction, PRIS includes a fairly large sample ($n = 284$) of "planned" but never (or not yet) built reactors. The IAEA states that a reactor is categorized as "planned" during the period "when a construction licence application has been submitted to the relevant national regulatory authorities" but construction has not yet begun (IAEA, 2019). However, inclusion into PRIS is evidently inconsistent with this criterion. For example, the Ninh Thuận NPP–which Vietnam had contemplated for nearly a decade until it was cancelled by a vote of Vietnam's National Assembly in 2016 (Ngueyn and Minh, 2016)–is included in PRIS yet no news reports indicate that a construction license application was ever submitted to the national regulatory authority (Toan and Khrennikova, 2014; Toan, 2015; Toan and Yamaguchi, 2016).

Conversely, PRIS omits twenty six proposed reactors that Berndt and Aldrich (2016) include from the historical record in the United States, which I append to my database for use in Chapter 3. Of these twenty six reactors absent from PRIS, I identify twelve with valid

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[1] `https://pris.iaea.org/PRIS/home.aspx`

[2] `https://pris.iaea.org/signin`

docket numbers from the U.S. Atomic Energy Commission, implying that an application for a construction permit was submitted. I conclude that PRIS most likely does not contain the global population of proposed but never built commercial power reactors.

In the time subsequent to my temporary access to the restricted data of PRIS, I have manually updated my database with data from the public-facing version of PRIS[3] and *Reference Data Series No. 2* (IAEA, 2019). In most cases, this entailed updates to the dates related to plant construction and retirement. However, it was also necessary to append four observations from China, which were not present in PRIS as of July 2018 (even as "planned" reactors). These are Zhangzhou 1 & 2 and Taipingling 1 & 2, which began construction in 2019 and 2020.

One final reactor which I have appended is an observation representing the original Bushehr 2 in Iran. Bushehr 1 & 2 were originally designed by Kraftwerk Union and began construction in 1975. Due to circumstances arising from the Islamic Revolution and the Iran-Iraq War, only Bushehr 1 was ultimately ultimately completed, after considerable delay and Russian assistance. PRIS contains an observation that refers to the Russian-designed reactor presently under construction which bears the official designation "Bushehr 2." This is a brand new reactor, built from a clean slate, rather than an effort to complete the original Bushehr 2. Therefore, I treat these two instances of "Bushehr 2" as separate observations.

PRIS does not clearly distinguish between "commercial" and "research" power reactors. For example, BOR-60—a sodium-cooled, fast breeder reactor (FBR) in Russia with a nameplate electric capacity of 12 MWe—is included, while Experimental Breeder Reactor II–a 20MWe American FBR–is excluded. Both were designed, built, and operated by state-owned scientific laboratories for non-commercial purposes. While both generated electricity that was exported to the grid, the electricity was fundamentally a by-product of the research.

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[3] `https://pris.iaea.org/pris/`

The boundary between "research" and "commerical" is somewhat blurry. For example, the Shippingport Atomic Power Station was not economically justified on its own commercial merits. Rather, its purpose was as a proof-of-concept for future commercial PWRs and to provide operating experience for the electric utility industry (Hewlett and Holl, 1989, p. 421). I argue that, while many aspects of a reactor like Shippingport are unrepresentative, its inclusion is necessary to view the full picture of the historical evolution of commercial NPPs.

Another category of reactor that blurs the lines of "commercial" are those which historically served dual purposes of electricity generation and plutonium production for nuclear weapons. The earliest GCRs built by Great Britain and France were designed explicitly for this purpose at some penalty to their economics; they nevertheless generated commercial quantities of electricity that were exported to the grid. State ownership of the electricity sector further blurs the line between "commercial" and "non-commercial" in these cases. Reactor designs in these families were later refined to improve their economics but there is not a clear "break" at which such reactors became purely peaceful endeavors in their fundamental design.

Lacking a clear definition by which to differentiate commercial power reactors from others, I elected to retain reactors present in PRIS but not append any which were absent except those identified above, all of which were unambiguously commercial in purpose and scale. To account for unexplained properties of reactors of questionable "commercial" nature, I manually coded various binary indicator variables (see Section A.2 below). My primary justification for retention of such reactors was to ensure accurate measurement of cumulative experience.

Therefore, the final data set consists of 1,087 observations (reactors) at 404 sites (power plants) in 50 countries (as defined by their present-day boundaries). Table A.1 tabulates the count of observations according to their status (planned, under construction, operational, etc.) as of April 6, 2021.

Status	**Count**
Planned	76
Planning Suspended	55
Planning Cancelled	172
Under Construction	51
Construction Suspended	18
Construction Cancelled	77
Operational	447
Permanent Shutdown	191
Total	**1,087**

Table A.1: Status of All Reactors in the Database, as of April 6, 2021.

A.1.4 Data Cleaning Procedures

Because the data in PRIS were provided by the owner of the NPP in question or by a governmental representative of the country in which it is located, PRIS suffers from internal inconsistencies in the coding of many of its variables. I employed my knowledge of the subject matter to clean up the data where inconsistencies were obvious. For example, Framatome changed its name to Areva during a restructuring in 2001, only to later change it back in 2018 after another restructuring. Reactors designed and manufactured by this company are not consistently labeled under a single name in the raw PRIS dataset. Similarly, I treat Rosatom—Rusia's state-owned monopoly in nuclear power plant construction and operation—as one-in-the-same firm as the Soviet Ministry of Medium Machine-Building, which was responsible for the Soviet nuclear power program. Rosatom came about through a series of restructurings after Chernobyl and the collapse of the Soviet Union. Rosatom retains the intellectual property and the Soviet manufacturing infrastructure related to nuclear power in Russian territory; it even occupies the same headquarters in Moscow as the old Soviet ministry.

Furthermore, missing data is a pervasive problem in the raw PRIS dataset. Where possible, I filled in missing data by referring to publications in nuclear engineering journals and documents released by nuclear regulatory agencies. Major supplementary sources of data will be noted in Section A.2 where applicable. In a handful of cases, missing data concerning particular reactors were supplied directly to me by personal contacts[4] in the nuclear industry.

A.2 Reactor-Level Data

A.2.1 Site Data

Name of the Site: As discussed in Section A.1.1, multiple reactors may be co-located at the same site. Generally, the string of text designating a shared site was taken directly from PRIS without alteration. However, in a handful of cases, I merged sites listed separately into a single site that better reflects the co-location of certain reactors. For example, PRIS lists the site for the Shippingport Atomic Power Station as “Shippingport” and the site for Beaver Valley Units 1 and 2 as “Beaver Valley." In light of the fact all three reactors were built immediately adjacent to each other, I edited the name of the Shippingport reactor’s site to “Beaver Valley” to unify all three reactors with a single coding. The purpose of this coding is to properly account for spatial autocorrelation in regressions that cluster reactors by site.

Total Reactors: For each reactor, I generate a count of the total number of reactors whose construction has been completed at that the same site.

N$^{\text{th}}$ Reactor: For each reactor, I identify whether it is the first, second, etc. reactor to be built at that site.

Tuplet Group: Many reactors were built as twins, triplets, or (in rare cases) higher order tuplets at the same site. I encode a variable that groups reactors together according to whether they are identical reactors built around the same time as a combined project.

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[4] Thanks, Dad.

Total Tuplets: For each reactor, I generate a variable that equals one if the reactor has no identical siblings, two if it has a twin, three if it belongs to a set of triplets, and so on.

N$^{\text{th}}$ Tuplet: For each reactor, I identify whether it is the first, second, etc. reactor to be built within its tuplet group.

Shared Start Dates: 149 reactors are listed as having begun construction on the same day as one or more others reactors at the same site; 132 of these are twin reactor units, along with one set of triplets, two sets of quadruplets, and one set of sextuplets. When multiple reactors are reported to have begun construction in tandem at a site, it atypical for those reactors to be completed on or around 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. For example, Calder Hall Units 1 and 2 are both listed as having begun construction on August 1st, 1953, but Unit 1 became operational four months earlier than Unit 2.

To account for this, I generate a control variable, which I abbrevate M_i, which ranks reactors at the same site which share the same start date. The reactor with the smallest unit number (or alphabetically earliest letter) is assigned a value of one on M_i, the second smallest (or alphabetically earliest) is assigned a value of two, and so on. A reactor which (A) has no twin or higher-order tuplet or (B) whose twin is listed as having begun construction on a different day is also assigned a value of one on M_i. Therefore, the interpretation of any coefficient on M_i refers to the marginal effect of increasing by one the number of reactors that began construction on the same date and the same site as reactor i but were prioritized over reactor i in the construction process.

A.2.2 Geographic Data

Subnational Region: Many (but not all) sites are matched with their current ISO 3166-2 code for principal subdivision (e.g. province or state). This work remains ongoing; special attention is needed regarding the matter of changes in subnational boundaries over time. For the purposes of Chapter 3, all American sites have been matched with the states in which they are located.

Country: Construction of the first observation in the dataset commenced in 1951, and several major changes in international borders have occurred since that time. For the purposes of the analysis in Chapter 1, a reactor's "country" is whichever national entity had territorial sovereignty over the site as of the year construction began. In particular, this means several reactors which began construction under the Soviet Union and Czechoslovakia but were finished after the dissolution of those countries are considered to be "in" their former countries. However, in post-Soviet countries, work on fourteen new reactors has begun, twelve in Russia and two in Belarus. For the purposes of country fixed effects and standard errors clustered by country, Soviet successor states are treated as distinct countries in these cases.

The identity of the country with territorial control over the site as of the years 1950 and 2020 are also coded, for expositional purposes and the benefit of future users of the data. In all cases, counties are coded according to their ISO 3166 Alpha-3 abbreviations.[5]

Latitude & Longitude: Latitude and longitude data were primarily drawn from the Global Power Plant Database by the World Resources Institute (Byers et al., 2019). Missing data were supplemented from Nucleopedia, a German-language wiki on nuclear power plants,[6] and a series of reports from Oak Ridge National Laboratory (Heddleson, 1972, 1973, 1974, 1975, 1976) on American NPPs.

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[5] `https://www.iso.org/iso-3166-country-codes.html`

[6] `https://de.nucleopedia.org/`

Local Climate: Chen and Chen (2013) provide a global map of Köppen climate classifications at a resolution of 0.5° by 0.5°. I match every NPP site with the nearest centroid of this grid, except where the centroid lies in the ocean or other large body of water. The data from Chen and Chen (2013) do not classify the climate of such cells and I instead match the site to the nearest centroid over land.

Cooling Water Salinity: The local source of cooling water is categorized, principally with respect to its salinity: ocean, brackish sea (principally the Caspian and Baltic Seas), estuary, freshwater, or municipal wastewater (a watersource unique to Palo Verde NPP).

A.2.3 Dates of Significance

Construction Start: These dates come directly from PRIS, which defines construction as having begun "when the first major placing of concrete, usually for the base mat of the reactor building, is carried out" (IAEA, 2019). For brevity, this event is sometimes called "first concrete." Site preparation proceeds first concrete, but data regarding the commencement of site preparation is not widely available, particularly because it can proceed regulatory approval.

Construction Suspension: 195 reactors in the sample have had their construction suspended (whether temporarily or permanently). The dates of such occurrences are partially available in PRIS; however, the data availability is incomplete and it is provided in the same field as the date of retirement from commercial operation. I have created a separate variable for the date of construction suspension to rectify this coding issue. Missing dates have been supplemented manually through case-by-case historical research, principally through consultation of issues of *Nucleonics Week*. I also retain a variable indicating the level of precision by which this date is known (day, month, or year) from my research.

Construction Restart: 22 reactors in the sample have resumed construction following a suspension. No dates of construction restart were provided by PRIS; all were gathered manually through case-by-case historical research. A variable indicating the level of precision by which these dates are known is also retained.

First Criticality: Criticality is "the state of a nuclear chain reacting medium when the chain reaction is just self-sustaining" (IAEA, 2018). For nuclear power plants, the first instance of criticality occurs prior to commercial operation, as part of the commissioning procedures and tests. These dates are provided by PRIS with no supplementation from other sources.

Grid Connection: The date of grid connection refers to "the date when the plant is first connected to the electrical grid for the supply of power" (IAEA, 2019). However, typically some time elapses after this event before the plant will be officially declared to be in commercial operation; trial operations and further tests are usually carried out. These dates are provided by PRIS with no supplementation from other sources.

Commercial Operation: The date on which a reactor is considered to be in commercial operation is "the date when the plant is handed over by the contractors to the owner and declared officially in commercial operation" (IAEA, 2019). These dates are provided by PRIS with no supplementation from other sources.

Retirement: The retirement date is defined as "the date when the plant is officially declared to be shut down by the owner and taken out of operation permanently" (IAEA, 2019). These dates are provided by PRIS with no supplementation from other sources.

A.2.4 Construction Economics

Gross Lead Time: I compute gross lead time as the difference in days between the construction start date and the date of commercial operation. For ease of exposition, I usually present this number in months ($\frac{days}{30.44}$), years ($\frac{days}{365.25}$), or the natural logarithm of months.

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.

To account for the problems arising from suspension of construction, I retain an indicator variable that takes on the value one for reactors which were suspended and a continuous measure of the number of months during which construction was suspended. In unreported regressions, I find that—after subtracting the months of suspension from the gross lead time—the length of the suspension period has no statistically significant marginal effect on net lead time over and above the predictive power of a binary indicator of whether construction was ever temporarily suspended for any length of time.

In Chapter 1, I use net lead time, although I refer to it as "lead time" or LT, for brevity. I wish to emphasize that *net* lead time is not intended to represent a "complete" measure of lead time for the purposes such as estimating LCOE or comparing the lead times of NPPs to the lead times of other technologies. *Gross* lead time, including periods of construction suspension, is the appropriate metric for those purposes. It may also be desireable to include planning and permitting phases, as in Aldrich (2010), for certain purposes. My purpose in defining lead time in this way is to generate an outcome metric that improves apples-to-apples comparisons of NPPs in order to understand why LT varies cross-nationally and over time. It would be unfair to compare to compare on the basis of gross lead time, for example, French and Soviet PWRs that began construction in 1980s. Many Soviet NPP projects were put on hiatus for macroeconomic and political reasons. If policymakers and industry participants wish to improve the the economics of NPP construction, one simple change they can make is to avoid suspending construction, insofar as they can help it.

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.

A.2.5 Firms Involved in Design, Construction, and Operation

NSSS Designer: PRIS provides the name of designer(s) of the nuclear steam supply system (NSSS). Extensive editing was performed by hand to ensure a single, consistent name for each firm. In cases where more than one firm is listed for a single reactor, the firm with more experience or holding the intellectual property is identified as the "primary" designer.

Turbo-Generator Manufacturer: PRIS provides the name of manufacturer(s) of the steam turbine / generator set (turbo-generator). Extensive editing was performed by hand to ensure a single, consistent name for each firm. The identity of the manufacturer of the turbo-generator was ultimately not used in any of the analyses described above.

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.

Lead Utility: PRIS only identifies the current, primary owner of each reactor. Therefore, I consulted other sources to identify the original utility in the case of NPP divestments in jurisdictions that underwent liberalization of their electricity markets. From this information, I generated a variable indicating whether the lead utility—typically, the single largest owner—was investor-owned (1) or state-owned (0) as of the date construction began. For utilities of mixed ownership, this variable takes on the value 0.5.

A.2.6 Reactor Typology

Reactor Type: I use the term "type" to encapsulate broad similarities in the principles of a reactor's design. The most common types are pressurized water reactors (PWR), boiling water reactors (BWR), pressurized heavy water reactors (PHWR), gas-cooled reactors (GCR), and light water graphite reactors (LWGR). All other types were aggregated into a category called "other" due to a sparsity of observations.

Reactor Family: I use the term "family" to classify reactors that have a shared evolutionary heritage. For example, all pressurized water reactors of Soviet or Russian origin are grouped into the VVER family[7] 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 and Sidorenko (1997) for the Soviet VVER and RBMK families. The CANDU family is identified in Garland (2016); I treat India as having branched off and established a separate family of heavy water reactors after Canada (the originator of the CANDU design) cancelled its cooperation on nuclear power in response to India's first nuclear weapons test in 1974.[8] Future research could improve upon this classification scheme by properly accounting for cross-fertilization in reactor design that has occurred in recent decades.

Reactors of unconventional and experimental designs that were never iterated upon are coded

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[7] All reactor models in this family begin with the letters VVER, a Russian acronym which basically translates to "light water reactor."

[8] This Indian family inherits the cumulative experience of the CANDU family associated with the two reactors in India for which Canada initially provided support.

as belonging to a family equal to their reactor model.

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.

Reactor Model: I use the term the name of the model assigned by the manufacturer, where applicable. Examples of model names assigned by the manufacturer include AP-1000, CP1, P4, OPR-1000, CNP-300, VVER-213, and ABWR. For standardized reactor designs, this classification comes as close as realistically possible to identifying "identical" reactors. However, for non-standardized designs, PRIS provides an abbreviated, generalized description of the reactor's design in place of a model name. For example, "WH 4LP (DRYAMB)" indicates that the reactor is a Westinghouse design with four primary coolant loops and the containment structure operates at ambient atmospheric pressure. Information about the containment design is inconsistently included in the IAEA coding of models, so I remove it and place it in a separate variable.

A.2.7 Technical Specifications

Capacity in Megawatts: PRIS offers four measures of the rated capacity: the rated net electric capacity as originally designed, the current rating of the net electric capacity,[9] the

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[9] A nuclear reactor's capacity may change over time as a result of uprates and downrates—modifications to the original design and/or changes in regulatory permissions.

current rating of gross electric capacity,[10] and the current rating of the thermal capacity of the reactor core. My ideal specification would select the rated thermal capacity as originally designed. Thermal capacity as is a more precise indicator of the inherent safety challenges of a larger reactor, whereas electrical capacity–while primarily a function of size–also reflects the thermodynamic efficiency of the plant. However, original thermal capacity is not available from PRIS. As a second-best, I use the original net electricity capacity, because it is a measure of the "original" size of the plant (prior to uprates) and because it lends itself to a more intuitive interpretation of the results. In any case, robustness checks revealed that none of results presented herein are sensitive to the specification of this variable.

Design Characteristics: PRIS includes over 150 variables that quantify or characterize technical details of a reactor's design. Notable variables include cooling method (e.g. cooling towers vs. once-through cooling), height and diameter of the reactor pressure vessel, average density of power per unit volume of the core, reactor outlet and inlet temperature, average core power density, number of steam generators, and number of steam turbines per reactor. A handful of variables are not particularly informative, as they are necessarily implied by a reactor's type, such as choice of moderator and coolant. Unfortunately, many other variables were left blank for a large number of the observations. Most notably, safety-relevant design characteristics are sparsely provided and inconsistently coded. Presently, the only safety feature with reasonable data coverage and a clean coding is the material used for the containment structure. More work is necessary to supplement and clean the current database to enable an analysis that directly examines safety features.

Standardization: I code every reactor as either standardized (1) or non-standardized (0). A reactor was determined to be standardized if the preponderance of the literature characterized it (or all reactors of its model) as standardized. Sources consulted include Gavrilas

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[10] Gross capacity is the amount of electrical power produced by the generator. Some of that power is used to operate the reactor and power other facilities at the plant. The amount of power exported to the grid is the net capacity.

et al. (1995), Goldberg and Rosner (2011), Lovering et al. (2016), Csereklyei et al. (2016), and back issues of *Nucleonics Week*. This dichotomous coding of standardization is not ideal, as standardization is arguably better characterized by a continuum of similarity or dissimilarity between two reactors. I generated such a continuous measure, drawing from within-model variation in design characteristics. However, in robustness checks, continuous measures of standardization were not found to contribute any meaningful explanatory power above and beyond that provided by a dichotomous indicator of standardization. Therefore, I adopt the dichotomous coding as my preferred measure of standardization.

Containment Design: I classify containment as falling into one of ten categories. These are listed in Table 1.5. Data coverage here is imperfect, as 108 reactors are classified as having an "unknown or other" design of containment. These are primarily early and experimental reactors, but it also includes twelve commercial-scale BWRs that cannot be classified as either Mark I, Mark II, Mark III. Further research is needed to close these gaps in the data.

A.3 Country-Level Data

GDP per Capita: I draw from the Maddison Project Database Bolt et al. (2018) for its historical estimates of GDP per capita. While the Maddison Project reports data for the former USSR and Yugoslavia, it does not desegregate East and West Germany. For these countries, I rely on data from Broadberry and Klein (2012).

Democracy: The "Polyarchy" index of electoral democracy provided by the Varieties of Democracy (V-Dem) Project (Coppedge et al., 2019) is my preferred measure of democracy. The V-Dem project an ongoing collaboration of "six Principal Investigators (PIs), seventeen Project Managers (PMs) with special responsibility for issue areas, more than thirty Regional Managers (RMs), 170 Country Coordinators (CCs), Research Assistants, and 3,000 Country

Experts (CEs)" who generate quantitative measures of the characteristics of government. It is currently headquartered at the University of Gothenburg.

In unreported robustness checks, I also use the Polity score of democracy/autocracy from Polity IV, a project of the Center for Systemic Peace Marshall et al. (2018).

Decentralization: I test three measures of decentralization. The first is a binary indicator of whether the country has a federal or unitary constitution as of the year in which construction begins. This is a fairly coarse measure, failing to capture more complex cases like Spain. Spain formally declares itself a unitary nation, but in practice has operated with a high degree of regional autonomy ever since the end of the Franco regime and the restoration of the monarchy. Conversely, the USSR considered itself a federation of several constituent republics, but—as a totalitarian regime—operated in a highly centralized manner in practice, up until its final years, over the course of which it ultimately dissolved.

A more fine-grained metric is the "division of power index" from V-Dem. This index measures whether local and regional governments exist, whether they have elected offices, and the extent to which elected local and regional governments can "operate without interference from unelected bodies at the local [and regional] level[s]." The V-Dem codebook is careful to stress that this variable does not measure the power of local and regional governments relative to the national government. It is better conceptualized as the degree of democratic control at the local and regional levels of government. However, the primary benefit of using this measure of decentralization is that it provides complete data coverage; no observations are dropped from the analysis on account of missing data from V-Dem. A severe downside is that it is highly collinear with Polyarchy (r=.91).

The richest measure of subnational political autonomy is from from the Regional Authority Index (RAI) by Hooghe et al. (2016). They evaluate the constitutions and political histories of individual countries and they systematically scored them on matters such as the role of subnational governments in approving constitutional change, whether the central government holds a veto over subnational decisions, and the autonomy of subnational jurisdictions in setting their tax base and rates. These scores are summed to generate indices along two dimensions of decentralization: self-rule ("the authority exercised by a regional government over those who live in the region") and shared rule ("the authority exercised by a regional government or its representatives in the country as a whole"). These two indices are then summed to generate a single, generalized measure of decentralization, which they call the Regional Authority Index (RAI). However, I only use the self-rule index, as it more closely pertains to the theory I elaborate in Section 1.1.7.

To increase coverage of the RAI data, I rely on the coding of self-rule from Sorens (2015) for South Africa. My final dataset matches an RAI self-rule score to 534 completed reactors, out of 637 total.

Regime Change: I rely on data from Polity IV to identify the dates and magnitudes of regime changes. I assign a value of 1 to a reactor if it was under construction (or suspended) during an episode of major regime change, and zero otherwise. I exclude relatively minor[11] "regime transition events," such as the resignation of U.S. President Richard Nixon, which corresponds to a small increase in the Polity score for the United States of America. The resulting binary indicator largely reflects the fall of Communism in Eastern Europe. However, it also captures the Iranian Revolution and the beginning and/or ending of military dictatorships in Spain, Latin America, Asia.

Geopolitical Region: Table 1.1 disaggregates summary statistics by four geopolitical regions. In assigning countries to these regions, I applied the the following judgments in ambiguous cases:

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[11] Specifically, I exclude all events for which the absolute value of the Polity IV variable REGTRANS is less than or equal to 1. This retains "major democratic transitions," "minor democratic transitions," "adverse regime transitions", and "state failures."

Certain capitalist countries in Europe are not members of NATO (Switzerland, Sweden, and Finland) or were not members of NATO as of the year construction began (Spain prior to 1982). These nations are nonetheless classified as part of the Western Bloc due to broad similarities to NATO nations in their political, economic, and cultural characteristics, as well as their choice of Western nuclear technology.

Slovenia, while under communist rule as part of Yugoslavia during the period when the Krško NPP was built, was not classified as part of the Eastern Bloc. As a result of Tito's diplomatic "split" with Stalin and his role in the foundation of the Non-Aligned Movement, Yugoslavia imported a Westinghouse design for its reactor rather than a Soviet one. Therefore, Yugoslavia/Slovenia was assigned to the reference region.

Twenty three reactors in Eastern Bloc countries have entered commercial operation after the collapse of communist regimes (including fifteen which were under construction during episodes of regime change). Although some of these countries subsequently joined NATO, observations in such countries are still classified as Eastern Bloc because Soviet technology was employed[12] and/or construction began prior to the collapse of communism.

East Asian countries were grouped separately from South Asian countries due to the relatively high lead times of NPPs built in India and Pakistan and relatively low lead times in East Asian nations, as compared to the global average. Because this categorization was explicitly motivated patterns in the outcome variable, it is more of a descriptive than explanatory variable. However, it should be noted that the cultural, historical, and economic differences between East Asia and South Asia are tremendous, beginning with their independent development as "cradles of civilization," separated by the largest mountain range on Earth.

Any country not assigned the Western Bloc, the Eastern Bloc, or East Asia was assigned to

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[12] With the exception of Romania, which imported a Canadian heavy water reactor design.

the reference category, which may be conceptualized as the Global South or the Non-Aligned Movement. Note that Argentina, Brazil, and Mexico are observers but not members of the Non-Aligned Movement.

A.4 Electricity Sector Restructuring

A mix of scholarly, historical, and technical sources were consulted to compile the data that identifies the presence/absence, nature, and timing of reforms to the electricity sector across jurisdictions.

For the United States, I chiefly rely on Davis and Wolfram (2012) to identify the dates of NPP unbundling. I cross-checked their dates of unbundling with contemporary reporting in industry periodicals and mass-market newspapers. For the dates of introduction of wholesale competition, I referenced the websites of American RTOs and ISOs, which usually provided historical timelines.

For Canada, I chiefly rely upon Clark and Leach (2005), supplemented by reference to news articles and company websites.

For the European Union, I started with Van Koten and Ortmann (2008) as a principal reference. However, they only identify dates of reform at an annual resolution, so I followed their sources cited to increase the temporal resolution to monthly.

Two sources are worth mentioning for their coverage of multiple countries, particularly those in the Global South and the former Soviet Union. The first is the series of Country Nuclear Power Profiles (CNPP) produced by the IAEA.[13] Among other topics, each CNPP provides detailed information for a single country on the status of nuclear power plants vis-a-vis the industrial organization of the larger electricity sector. The second noteworthy source

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[13] `https://cnpp.iaea.org/pages/index.htm`

was Vagliasindi and Besant-Jones (2013), who—among their cases studies of countries with nuclear power plants—were Argentina, Brazil, Czechia, South Korea, and South Africa.

A.5 Historical Regulatory Data from the United States

A.5.1 Regulatory Guides

The U.S. Nuclear Regulatory Commission (NRC) provides the following descriptions of its regulatory guides on its website:[14]

> *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

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[14] `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 A.2: Search Terms to Identify Regulatory Guides of a Clerical Nature

universe of regulatory guides—including all past versions and their month of issuance—is digitized and publicly available from the NRC’s website.

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 A.2.

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.

A.5.2 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[15] 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 3.6 and 3.6. 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

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

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):

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

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 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.

A.5.3 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 Chapter 3, 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,[16] which I double-checked using the search function on `federalregister.gov`. The survey is presented in the form of Table A.3. 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 3.5.1. 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 3.8 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 the Federal Register which announce

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

final rules modifying it.[17] 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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[17] *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 A.3: List of Revisions to 10 CFR §50.73

A.5.4 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.

A.6 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.

A.6.1 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.

Among the individual policies collected by Caughey and Warshaw (2015) is the adoption of state companion laws to the National Environmental Policy Act (NEPA). This variable is binary: one if such a law was adopted and in effect, zero if not.

A.6.2 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.[18]

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 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).

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[18] 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.

A.6.3 Real Personal Income

To measure differences in economic prosperity across states and over time, I draw from the estimates of real personal income from Klarner (2013). The inflation adjustment uses the Consumer Price Index (CPI-U), with base years of 1982-1984.

A.7 U.S. County-Level Data

I append the dataset of Berndt and Aldrich (2016), which contains data on the counties in which proposed and actual American nuclear power plants are located.

Appendix B

Methodological Appendix to Chapter 1

B.1 Exogeneity of Political Institutions

In all of the specifications described in Chapter 1, I take democracy and decentralization to be exogenous. Political institutions are almost surely exogenous to nuclear power plant design and construction activity. For most nations in the sample, the constitutional design was chosen long before the discovery of nuclear fission in 1938 and it has continued with only modest changes up to the present day. In the rare cases where it changed during the sample period, the lead time in constructing nuclear power plants was almost certainly unrelated to the change.[1] One may argue that the dissolution of the USSR was meaningfully hastened by the Chernobyl disaster—a theory which has been endorsed by ex-President Mikhail Gorbachev.[2] However, modeling this historical trajectory is beyond the scope of the present work. All regime changes are assumed to be exogenous for my purposes.

In theory, countries which undergo regime change or constitutional reform should offer fertile

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[1] For example, Czechoslovakia, a federal nation, dissolved and become two unitary nations on the basis of ethnic differences.

[2] Gorbachev, Mikhail. 17 April 2006. "VIEW: Turning point at Chernobyl" `https://www.gorby.ru/en/presscenter/publication/show_25057/`

ground for causal inference. However, too few of the observations lie on both sides of major regime changes or constitutional reforms within a single country, limiting the statistical power of a hypothetical event study. Furthermore, for NPPs which began construction under one regime and finished under another (e.g. the Soviet Union and Soviet successor states), it is hard to disentangle the effect of economic upheavals commonly associated with regime change from the effects of the new regime *per se*.

B.2 Serial Construction

149 reactors are listed as having begun construction on the same day as one or more others reactors at the same site; 132 of these are twin reactor units, along with one set of triplets, two sets of quadruplets, and one set of sextuplets. 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. For example, Calder Hall Units 1 and 2 are both listed as having begun construction on August 1st, 1953, but Unit 1 became operational four months earlier than Unit 2.

To account for this, I generate a control variable, M_i, which ranks reactors at the same site which share the same start date. The reactor with the smallest unit number (or alphabetically earliest unit letter) is assigned a value of one on M_i, the second smallest (or earliest) is assigned a value of two, and so on. A reactor which (A) has no twin or higher-order tuplet or (B) whose twin is listed as having begun construction on a different day is also assigned a value of one on M_i. Therefore, the interpretation of any coefficient on M_i refers to the marginal effect of increasing by one the number of reactors that began construction on the same date and the same site as reactor i but were prioritized over reactor i in the construction process.

B.3 Abandoned Construction and Possible Selection Bias

Ninety five reactors listed in PRIS began construction but have never been completed, as of April 6th, 2021, due to suspensions or cancellations. This suggests the possibility of selection bias, as reactors which are taking longer to build for reasons related to decentralization (or any other explanatory variable of interest) are more liable to have their construction abandoned due to poor economics. Table B.1 summarizes these observations by country and lists known or likely explanations for the abandonment of construction. Abandoned construction can be broadly grouped into three typologies: conditions in federalist democracies (43 observations), the fall of communism and its geopolitical fallout (35 observations), and regulatory/political decisions at the national level in democracies (11 observations).

Nations transitioning out of communist regimes tended to suspend or abandon construction on their reactors for the same set of reasons: shortfalls in financing, a collapse in electricity demand, and the fresh memory of Chernobyl in the minds of voting publics. In such cases, I argue that the non-completion is attributable to regime change. In former East Germany, the newly reunited German government shut down the operating reactors and cancelled those under construction on the grounds that Soviet-designed reactors did not meet West German safety standards. The abandoned reactor in North Korea was being supplied by the United States as a condition of a 1994 agreement to convince North Korea to remain a party to the Non-Proliferation Treaty. Construction began in 2002 and ended a year later when the agreement broke down.

Country	**Count**	**Known or Likely Reasons**
Austria	1	national referendum banning nuclear power
Brazil	1	corruption scandal
Bulgaria	2	fall of communist regime
Cuba	2	termination of Soviet aid
Czechoslovakia	2	fall of communist regime
East Germany	5	German re-unification
Iran	1	suspended during Islamic Revolution, damaged during Iran-Iraq War
Italy	3	national referendum banning nuclear power
Japan	2	in limbo due to post-Fukushima regulatory environment
North Korea	1	breakdown of diplomatic agreement
Philippines	1	national executive decision
Poland	2	fall of communist regime
Romania	3	fall of communist regime
Russia (post-1991)	1	energy geopolitics
Spain	4	national legislative decision
Soviet Union	4	short-term response to Chernobyl disaster (RBMK design or other safety issues)
	14	fall of communist regime
	1	suspended after Chernobyl disaster, later restarted, cancelled after Fukushima-Daiichi disaster
Taiwan	2	national executive decision
United States	42	cancellation by utility
West Germany	1	permission to operate denied by state government
World	**95**	

Table B.1: Reactors for which Construction was Abandoned or is Presently Suspended

However, the slew of cancellations by utilities in the United States, primarily in the 1970s and 1980s, do present a serious selection concern. The proximate motive for these voluntary cancellations, by and large, were economic factors: budget overruns, schedule slippage, and downward revisions in electricity demand forecasts. However, the effect of the political and regulatory environment on schedule slippage is a precisely the causal mechanism under study.

The abandoned reactor in West Germany presents similar a selection concern. The SNR-300, a fast breeder reactor, began construction in 1973 near Kalkar, North Rhine-Westphalia. While its cancellation can be formally attributed to the decision in 1990 of the state government to deny permission to operate, substantial delays had already occurred due to local public protest and regulatory intervention by the state government. Had it instead been permitted to operate, it would register in the data as another observation with long lead time in a nation with high decentralization.

The expected selection bias due to the U.S. and West Germany is negative. In general, utilities are more likely to abandon construction on reactors that are behind schedule than those for which construction is proceeding smoothly. To the extent that the treatment (decentralization) has a causal effect on the outcome (lead time), it is expected that higher levels of the treatment cause higher rates of attrition from the study (failure to complete construction). Reactors that finish construction are in this sense a selected sample of "survivors."

In Table B.2, I report the results of two probit models, the first taking suspension of construction as the outcome of interest and the second evaluating completion[3] I find that neither democracy nor decentralization are statistically meaningful predictors of either outcome, although GDP per capita is meaningfully associated with the probability that a reactor is suspended. Moreover, suspension and completion are much more strongly predicted by momentous events, namely nuclear power accidents and regime change. I take this as evidence

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[3] Suspension and completion are not mutually exclusive outcomes, as fourteen reactors have been suspended but were later completed.

Dependent Variable (1): 1 if ever suspended, 0 otherwise
Dependent Variable (2): 1 if ever completed, 0 otherwise

	(1)	(2)
GDP per capita	**8.7%**	**-8.8%**
one S.D. increase in $ln(GDPpc_{c,y})$	(1.80)	(-1.58)
Democracy	**-5.1%**	**5.2%**
one S.D. increase in $Dem_{c,y}$	(-1.20)	(1.21)
Decentralization	**4.1%**	**-3.7%**
one S.D. increase in $Dec_{c,y}$ (V-Dem)	(1.10)	(-0.93)
Investor-Owned Utility	**-7.5%**	**7.3%**
IOU_i	(-1.77)	(1.63)
Three Mile Island Accident	**-1.8%**	**0.0%**
under construction on 3/28/1979	(-0.42)	(0.00)
Three Mile Island Accident × USA	**27.1%**	**-24.5%**
under construction on 3/28/1979 in the USA	(6.03)	(-6.60)
Chernobyl Disaster	**13.7%**	**-12.5%**
under construction on 4/26/1986	(2.13)	(-2.01)
Chernobyl Disaster × USSR	**7.9%**	**-4.1%**
under construction on 4/26/1986 in the USSR	(1.64)	(-0.82)
Fukushima Daiichi Disaster	**10.1%**	**-8.5%**
under construction on 3/11/2011	(1.26)	(-0.97)
Regime Change	**34.6%**	**-27.8%**
under construction during regime change	(4.90)	(-3.51)
Observations	774	732

Average marginal effects on the probability of the outcome in **bold.** (t-statistics in parentheses.)
Reactors presently under construction are excluded from column (2).

Table B.2: Predictors of Construction Suspension and Completion that selection bias—insofar as it might bias downwards the coefficients on democracy and decentralization—is of minimal concern. Selection bias is almost certainly present in the coefficients on regime change and nuclear power accidents, the correction for which I discuss in Section B.4. The regressions presented in Section 1.4 were also estimated with the Heckman correction Heckman (1976), but these are not reported here because the differences in the results are quantitatively negligible.

B.4 Modeling the Effect of Major Events

The three largest nuclear accidents—namely, those at Three Mile Island (TMI), Chernobyl, and Fukushima Daiichi—are widely recognized among industry observers as producing episodes of regulatory instability and political difficulty for nuclear power plants under construction. Additionally, I consider the effect of regime change, which is a leading cause of construction suspension and cancellation, as noted above.

It would be desirable to control for these events, even if they are uncorrelated with the variables of interest, for the sake of improving the precision of the model. However, there is a problem of endogenous selection into treatment (i.e. being under construction during an event). Consider two reactors that are identical on all observable characteristics and began construction on the same date.[4] If one reactor finished construction prior to the Three Mile Island accident while the the other finished after, there necessarily must exist some unobserved characteristic of the second reactor that caused it to take longer and therefore be exposed to the political/regulatory aftermath of the accident. For this reason, the estimated effect on LT is necessarily biased upwards.

To resolve this endogeneity issue, I instrument for selection into treatment with a non-

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[4] Further assume that these reactors are located at separate sites, and therefore are not being built according to a staggered schedule.

	First Stage F Statistic
Three Mile Island Accident *under construction on 3/28/1979*	219
Three Mile Island Accident × USA *under construction on 3/28/1979 in the USA*	7058
Chernobyl Disaster *under construction on 4/26/1986*	55
Chernobyl Disaster × USSR *under construction on 4/26/1986 in the USSR*	318
Fukushima Daiichi Disaster *under construction on 3/11/2011*	7.25
Regime Change *under construction during regime change*	81
Observations	556

Table B.3: Relevance of Instruments for Column (2) of Table 1.8

linear function of the date on which construction began. To construct this instrument, I first set aside reactors which began construction after a given event. With the remaining reactors, I estimate a binary probit model that regresses selection into treatment on the date construction began. I then generate the predicted probabilities of having been still under construction as of the date of the event. For the reactors that began construction after the event, I assign a predicted probability of zero. For such reactors, the event is not an unanticipated shock.

This procedure generates the instrumental variables for selection into treatment by major events. F statistics for the first stage of the regression reported in Column (2) of Table 1.8 are reported on Table B.3. Nearly all of them are extremely large (greater than 50), which the exception of the instrument for being under construction during the Fukushima

Daiichi disaster. The weak relevance of the instrument may be an artefact of four long-delayed reactors which began their construction prior to the year 2000, had their construction suspended for a decade or longer, and only resumed construction much later.[5] Thus, the binary probit model estimates that reactors from this era have a non-trivial probability of exposure to the Fukushima Daiichi disaster.

I argue that the exclusion criterion is satisfied for two reasons. First, the events in question are unanticipated, so they cannot have a casual relationship that flows backwards in time to influence start date. Second, the instruments have an unusual non-linear and step-wise relationship with time; they are unlikely to correlate with other possible unobserved variables that may trend over time.

B.5 Measuring Cumulative Experience

The decision of how to quantify cumulative experience for the purpose of estimating learning-by-doing raises numerous issues. By convention in the literature on electricity generation technologies, the unit of measure of cumulative experience is the megawatt Berthélemy and Escobar Rangel (2015); Rubin et al. (2015). For example, utility-scale solar and wind farms consist of so many wind turbines and solar panels that it is not particularly important to count the discrete number of panels and turbines. However, I argue that the megawatt is a less theoretically applicable unit of measure for nuclear power plant construction. Nuclear reactors are quite lumpy in nature due to their (traditionally) massive size. In my view, a firm which has built ten 200MW reactors has had five times as many opportunities for learning as a competing firm which has built a pair of 1000 MW reactors. By contrast, whether 2000 MW of solar panels are divided up into two or ten solar farms does not matter at all to the factory which produced the panels; the only difference is that there may be

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[5] The reactors are Watts Bar 2, Bushehr 1, Atucha 2, and Kalinin 4.

some modest economies of scale in the installation process for larger solar farms.

I draw on the work of Gavrilas et al. (1995) and Sidorenko (1997) to conclude that a credible measure of cumulative experience should (1) be global in scope, (2) recognize technological spill-overs between associated firms, and (3) account for the common evolutionary heritage of related reactor models. I argue that reactor family, as I define it in Appendix A.2, best fits these criteria.

A global, rather than national, measure of cumulative experience is appropriate because most firms involved in nuclear reactor design and component supply are multinational corporations. Eight of the top ten most successful[6] families have "offspring" in more than one country; these eight families account for 85% of the observations. Experience gained by a firm in one country should, for the most part, be transferable by that firm to the business it does in another country. Furthermore, knowledge disseminates globally through organizations such as the International Atomic Energy Agency and OECD Nuclear Energy Agency.

Firms in the nuclear industry frequently license intellectual property to one another and even collaborate in reactor design, but they tend to do so within small networks that are, for the most part, stable. Reactor type is too broad of a criterion, as it would imply technological spill-overs between an American firm like Westinghouse and the Soviet Ministry of Medium Machine Building. Both built PWRs, but due to geopolitics, each firm developed its own PWR design independently.

Reactor model would be too narrow a criterion, because that would imply cumulative experience is entirely forfeited when a firm develops a new model. While economies in serial production of identical models almost surely enhances productivity, I am primarily interested in the learning that has occurred (if any) over the seven decades during which nuclear fission has been deployed for commercial electricity generation. Reactor models are contin-

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[6] Where I define success as having the most completed reactors associated with a family.

uously revised and replaced on comparatively shorter time-scales. For the 91 models that were built more than once, the average gap between the date on which construction on the first reactor of that model began construction and the date on which the last reactor of that model began construction was 4.5 years. By comparison, the average reactor takes longer than that to build, at a global average 7.4 years. This implies learning-by-doing has a very short time window within which to be relevant to other reactors of the same model. Instead, I argue that the benefits of learning-by-doing (if they exist) have the greatest impact on newer models within the same family.

In unreported regressions, I tested whether the effect of cumulative experience is sensitive to defining cumulative experience with a delay period between when construction begins on a reactor j and when "knowledge" is gained for the purposes of reactor i. The results were found to be robust to several possible delay periods, but the best model fit was achieved with zero delay. Therefore, I adopt zero delay as my preferred specification.

I transform the raw count of all reactors meeting the inclusion criteria (i.e. having begun construction prior to reactor i and being within the same reactor family) using inverse hyperbolic sine (IHS or $sinh^{-1}$) transformation. The inverse hyperbolic sine of a variable x is approximately equal to $ln(2x) = ln(x) + ln(2)$ for large values of x, but for small values of x it differs–chiefly in the fact $arcsinh(0) = 0$, whereas $ln(0)$ is not defined. For several of the observations, it takes on a value of 0 in the measure of cumulative experience. While a more familiar solution is to take the transformation $ln(x + 1)$, econometricians recommend IHS Burbidge et al. (1988). Bellemare and Wichman (2019) provide a brief summary of how to interpret IHS coefficients. When the value of an untransformed variable is greater than 10, IHS coefficients are essentially equivalent in interpretation to the coefficients on log-transformed variables.

B.6 List of Symbols

Table B.4 provides a list of all symbols for variables used in Equations of Chapter 1.

Abbreviation	Full Description
LT_i	Lead time of the reactor in months, net of any months of suspended construction
$\widehat{LT_i}$	Predicted value of LT_i, conditional on design characteristics (see Section 1.3.1)
$Dem_{c,y}$	index of democracy in country c as of year y
$Dec_{c,y}$	index of decentralization in country c as of year y
$GDP_{c,y}$	GDP per capita in country c as of year y, in 2011USD
$Spec_{s,i}$	any of S design characteristics and specification variables for reactor i
MW_i	net electric capacity (original design rating) of reactor i
OTC_i	takes on the value 1 if reactor i uses once-through cooling, and 0 otherwise
Pu_i	takes on the value 1 if reactor i was built primarily for the co-generation of plutonium for weapons, and 0 otherwise
IOU_i	takes on the value 1 if reactor i lead utility was investor-owned, 0 if state-owned, and 0.5 if of mixed ownership
$NumUtil_c$	number of utilities appearing in the dataset for country c
M_i	a control for measurement error related to multi-unit construction (see Appendix B.2)
δ_t	fixed effect for reactor type t
δ_f	fixed effect for reactor family f
δ_m	fixed effect for reactor model m
μ_c	fixed effect for country c (as of the year reactor i began construction)
ν_y	fixed effect for year y (year in which reactor i began construction)
ξ_y	any of several indicator variables that takes on the value 1 if reactor i was under construction during event x, and 0 otherwise (see Appendix B.4)
ε_i	error term

Table B.4: Abbreviations and Symbols used in the Econometric Specifications