Codification Creep*

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RESEARCH SUMMARY. We propose that experienced organizations face a phenomenon we refer to as *codification creep*: the accumulation of highly transferable but rigid explicit knowledge that crowds out the use of tacit knowledge needed to execute and adapt quickly. Analyzing data from 598 nuclear power plant construction projects worldwide between 1951 and 2016, we find that general contractors become slower with experience: each subsequent plant built around a specific reactor model takes over 18 days longer to complete, and unexpected rain slows experienced contractors further. Interviews and archival records illustrate the codification creep underlying these findings. To self-disrupt codification creep, we show that organizations can introduce planned novelty—by intentionally switching to a new containment building technology—to counteract the drag of past experience.

MANAGERIAL SUMMARY. More experience can sometimes lead to slower projects. We identify a hidden trap called *codification creep*: the tendency to accumulate documents like manuals and checklists from past projects that stifle an organization and crowd out on-the-ground intuition needed to adapt. Our study of 598 nuclear plant construction projects finds that general contractors with more experience building plants for a specific reactor model become slower on future projects, especially when they face unusual weather conditions. To break out of the trap, managers can deliberately change a part of the project to force an organization to break from what was previously codified and instead rely on their intuition.

KEYWORDS. Codification, Organizational Experience, Tacit Knowledge; Explicit Knowledge; Adaptability; Transferability; Novelty; Nuclear Energy

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1. INTRODUCTION

A foundational premise in strategy is that organizations improve efficiency and speed as they accumulate experience, a phenomenon captured by the classic learning curve (Argote et al., 2021; Argote & Epple, 1990; Arrow, 1962; Levitt & March, 1988; Wright, 1936). Organizations seek to leverage knowledge gained from past projects and apply it to subsequent endeavors to execute those more efficiently. This perspective relies on two assumptions. First, that remembering what was learned is essential to realizing its benefits: without care for retaining knowledge in organizational memory (Walsh & Ungson, 1991), an organization risks knowledge depreciation or organizational forgetting (Argote, 1999; Darr et al., 1995). Second, that future activities will closely resemble past activities, ensuring the applicability of accumulated knowledge to the future (Thompson, 2007): this underpins the logic of "replication as strategy," where an organization applies its practices across similar contexts (Winter & Szulanski, 2001).

Conversely, research on organizational inertia suggests that experience can breed rigidity. As organizations succeed, they tend to formalize the processes that led to their success, fostering routines and structures that resist change (Balasubramanian & Lee, 2008; Hannan & Freeman, 1984). This literature argues that accumulated experience can become a liability, creating "core rigidities" (Leonard-Barton, 1992) that inhibit adaptation to novelty (Benner & Tripsas, 2012). This presents a fundamental theoretical tension: How can experience simultaneously drive efficiency and foster the rigidity that ultimately undermines those gains? We argue that reconciling this tension requires understanding the mechanism by which experience, which would otherwise result in efficiency gains, transforms into rigidity instead.

We introduce the concept of *codification creep* to explain this transformation, revealing a paradox in how organizations seek to benefit from their past experience. Organizations face dual imperatives: to maximize the retention of knowledge for future use, they seek to codify what can be codified into more durable explicit forms, like written records (Winter & Szulanski, 2001; Zander & Kogut, 1995); to align future use to this retained knowledge, they standardize what can be standardized so that future projects will be as similar as possible to past projects. The critical issue is the *routinization* that follows: the translation of explicit knowledge into routines (Nelson & Winter, 1982). To realize the benefits of its explicit knowledge towards a future standardized project, an organization must organize around that explicit knowledge by adapting its structures, processes, and coordination mechanisms to it. For instance, consider if the records from a past project indicated there was idle time because a specific input was not available at the specific time it was needed: the next project could move faster by prescheduling delivery of that input to arrive at the specific time past records suggested it would be needed. This routinization is how, in principle, an organization derives efficiency gains on a subsequent standardized project. However, this organizational routinization comes with a cost. Tailoring the organization to be maximally efficient at executing on the basis of past explicit knowledge can create rigidity that crowds out its use of its tacit knowledge (Polanyi, 1966); this rigidity can impair both the coordination of expected but tightly interdependent tasks (Nonaka, 1994; Puranam et al., 2012) and the flexibility needed to adapt to novel conditions (Feldman & Pentland, 2003).

Our theory of codification creep helps explain a striking puzzle observed in the global nuclear power plant construction industry. General contractors—firms responsible for the conventional civil engineering surrounding the pre-manufactured nuclear reactor, rather than anything specific to nuclear technology itself—have suffered for decades from protracted construction timelines lasting on the order of years or decades. For instance, Southern Company began construction of a third unit at the Alvin W. Vogtle Electric Generating Plant in 2009, expecting it to enter service in 2016. Seven years might already seem excessively long. In reality, it took fourteen years, twice as long as expected, not completing until 2023. These extended timelines result in significant cost overruns that devastate their financial returns (Eash-Gates et al., 2020) and damage the perceived viability of nuclear as an alternative to fossil fuels. With every incentive to learn from their experience and become more efficient, the industry meticulously documented learnings from past projects and sought to standardize the reactor models that they use in their projects. Despite these efforts—or more precisely, *because* of these efforts—we find the opposite of the conventional learning curve.

In our analysis of 598 nuclear power plant construction projects initiated worldwide between 1951 and 2016, we find that general contractors systematically get slower the more experience they accumulate building plants around a specific reactor model. The results reveal a robust *negative* learning curve consistent with the theory of codification creep: on average, each subsequent plant built using the same reactor model takes over 18 days longer to complete. In further support of the theory, we find that more experienced firms suffer disproportionately longer delays from unplanned novelty: specifically, the unexpected environmental shock of unusually heavy rainfall during construction. Given that these firms only become more experienced over time, their future beyond this study might appear hopeless. However, we argue that a pathway exists to disrupt codification creep and the rigidity that follows: the introduction of planned novelty can force an organization to forego reliance on explicit knowledge and instead rely on its tacit knowledge. We find that firms building a plant where they intentionally switch to a new containment building technology are able to build that plant faster the more experience they bring. A program of qualitative interviews and archival case studies further illustrates the role of codification creep in this slowdown of the industry.

This study makes several contributions. Most importantly, our theory of codification creep advances the integration of organizational learning and inertia literatures by identifying the mechanism through which experience transforms into rigidity. We provide further evidence critiquing the assumed benefits of the learning curve by demonstrating how the organizational structures designed to leverage past knowledge can paradoxically degrade performance. We also offer a prescriptive insight: deliberately injecting planned novelty can mitigate these negative effects, suggesting that a degree of exploration may be necessary to preserve the ability to effectively exploit existing capabilities (March, 1991). Our concluding discussion extends these insights to drive broader implications for the adjacent literatures on time compression diseconomies (Dierickx & Cool, 1989) and transaction cost economics (Williamson, 1985).

2. THEORETICAL DEVELOPMENT

Organizational experience can underpin performance improvements like greater efficiency, speed, and productivity. Learning-by-doing generates two broad forms of organizational knowledge: tacit and explicit. Tacit knowledge comprises unwritten, experience-based know-how embedded in an organization's people and processes (Nelson & Winter, 1982). As Polanyi (1966, p. 4) noted, "We know more than we can tell." Tacit knowledge is powerful largely because it is dynamic and plastic (Leonard-Barton, 1995); it is cultivated through interaction and experimentation (Nonaka & Takeuchi, 1995), allowing employees to adjust their actions based on real-time feedback and cues (Feldman & Pentland, 2003). In contrast, explicit knowledge is knowledge that has been formalized and articulated. It takes the form of written procedures, checklists, blueprints, databases, and other tangible artifacts (Zander & Kogut, 1995). To realize future efficiency, organizations must ensure that past knowledge, whether tacit or explicit, is both *remembered* and *relevant*, and then *rendered* into future action.

2.1. Codification Creep

We now present our theory of *codification creep*: the accumulation of explicit knowledge (codification) towards a repeated project (standardization) and the subsequent adaptation of the organization (routinization). While the phrase codification creep may sound negative, codification creep need not have an adverse consequence in and of itself. To the contrary, organizations allow or even foster codification creep on its promise of improved productivity or speed. But the focus of this study will be its critical downsides. We begin by describing the three processes that make up codification creep: codification, standardization, and routinization.

2.1.1. Codification: Retaining Explicit Knowledge

The first imperative that organizations face is retaining knowledge for future use. Organizations risk forgetting knowledge or its depreciation without active management of organizational memory (Argote, 1999; Darr et al., 1995; Walsh & Ungson, 1991). For instance, Cattani, Dunbar, and Shapira (2013) examine how valuable knowledge can be lost in the absence of a knowledge management process for retention. Because tacit knowledge is inherently ephemeral—residing in the minds of individuals and vulnerable to staff turnover (Eckardt et al., 2014) or the passage of time (Epple et al., 1996)—organizations seek to codify what can be codified into more durable explicit forms. This involves taking the tacit knowledge from past projects and articulating it into explicit artifacts ranging from paper archives of invoices to digital renderings of previous designs. We use the term *codification* to refer to the organization process of generating and storing explicit information. While the literature on strategic alliances prominently features codification (e.g., Hanisch et al., 2025; Heimeriks et al., 2012, 2015; Keller et al., 2021), surprisingly little research considers its intra-organizational implications.

A core argument of this theory is that organizations naturally accumulate explicit knowledge disproportionally to the rate at which they accumulate tacit knowledge. This argument rests on two underlying drivers. First, explicit knowledge is naturally more durable than tacit knowledge (Zander & Kogut, 1995), making it easier to preserve over time and move across space, thus facilitating knowledge transfer and replication (Kale & Singh, 2007; Zollo & Singh, 2004). Written records can be shared across teams and persist long after the individuals involved depart. Second, recognizing this durability, organizations actively prioritize capturing experience in explicit forms. Even amidst prospective uncertainty about whether current experience will reduce future costs (Leiblein et al., 2023), we posit that organizations err towards codification to maintain the option value of using that knowledge. Typically, this is prudent. For example, Toyota famously invested heavily in codifying its production system into manuals and training programs to facilitate its transfer across different plants (Dyer & Nobeoka, 2000).

However, codification has a fundamental limitation: not every aspect of a skill or process can be fully specified (Hadjimichael et al., 2024). Miller, Galanter, and Pribram (1960) illustrate this with the landing of an airplane: a novice might memorize the steps quickly, but knowing the steps would not enable an unexperienced person to land the plane safely.

2.1.2. Standardization: Aligning Future to Past

The second imperative that organizations face is ensuring the relevance of retained knowledge. The presumption is that explicit knowledge from the past is most relevant if the future project is as similar as possible to the past project. Thus, organizations have an incentive for *standardization*, by which we mean they intentionally pursue future projects as similar as possible to past projects so that the specifications and assumptions embedded in their explicit knowledge apply to the future project. Standardization often involves deploying a fixed template across projects with as little modification as possible. By standardizing the parameters of future projects, organizations seek to maximize the applicability and utility of the explicit knowledge, further incentivizing codification. Consider Intel during its 1990s heyday. Intel required that every subsequent fabrication facility copy the original in exacting detail, from the make and model of equipment down to the plumbing. This standardization meant that engineers at one facility could document a manufacturing process, and different engineers at another facility could follow those instructions to reliably implement the same process at another.

However, standardization has its limitations. First, not every aspect of a complex project can be standardized. For example, consider enterprise software for electronic health care records. Even though large hospital systems have sought to standardize them, the realities of patient care often require ad hoc deviations to suit the idiosyncratic needs of different medical specialties, e.g., a single standardized template of a health record with fixed data fields cannot apply everywhere because the fields required to document trauma surgery are functionally incompatible with those needed for psychiatric care. Second, frictions may arise if the tasks are tightly interdependent with one another (Raveendran et al., 2020). A slight deviation in one task can create cascading effects for the efficacy of the other tasks.

2.1.3. Routinization: Translating Explicit Knowledge to Action

To realize the benefits of explicit knowledge from the past in a standardized future project, the explicit knowledge must be translated into action. This translation involves what we term *routinization*: the adaptation of organizational structures, processes, and coordination mechanisms to align with explicit knowledge (Helfat & Winter, 2011; Nelson & Winter, 1982). In other words, explicit knowledge is inert until the organization chooses to organize around it: this choice is, in some sense, deliberate (Zollo & Winter, 2002). This routinization process is how *codification*, the accumulated explicit knowledge, *creeps* into the organization itself.

Routinization is where and how, in principle, an organization derives efficiency gains on a subsequent standardized project. For example, IT teams seek to resolve server outages as fast as possible. As such, the routines mobilized in the event of a server outage are the direct result of explicit knowledge from past outages: the resolution steps for a server outage are often encoded into automated ticketing workflows and an explicit "runbook" that dictates which IT staff member should be pulled and when each should act. Rather than relying on ad hoc troubleshooting on the fly, an IT team routinizes around the explicit knowledge they gained from the past to act faster the next time around.

To be more precise, the efficiency gains from routinization stem primarily from reducing the need for active coordination and information processing between agents during execution (Galbraith, 1973; March & Simon, 1958; Thompson, 1967). In the language of organization design, routinization attempts to minimize what Puranam et al. (2012) refer to as epistemic interdependence, a situation where one actor's optimal choice depends on a prediction of another actor's choice. When epistemic interdependence exists, coordinating action requires costly or time-consuming information processing activities like communication or mutual observation. By instead relying on architectural knowledge of how the components of a system are related (Baldwin & Clark, 2000; Henderson & Clark, 1990), routinization seeks to eliminate this need by creating organizational silos and modular structures to execute tasks independently without back-and-forth coordination (Baldwin & Clark, 2000; Sanchez & Mahoney, 1996).

However, the above account describes an idealized situation. As we describe next, routinization as a part of codification creep can also lead to quite destructive consequences.

2.2. Codification Creep and Organizational Rigidity

In principle, in stable environments where future projects perfectly mirror the past, the combination of codification, standardization, and routinization should yield significant efficiency gains, consistent with the classic learning curve (Argote & Epple, 1990). Going further, Eisenhardt, Furr, and Bingham (2010) note that organizations often drift toward favoring efficiency regardless of whether that is optimal. However, these processes come with a potentially significant risk. Aggarwal, Posen, and Workiewicz (2017) highlight this fundamental trade-off: the very same micro-foundational processes that aggregate into efficient organizational capabilities also set the boundaries of the firm's adaptive capacity. Tailoring the organization to be maximally efficient at executing can impair both the coordination of interdependent tasks and the flexibility needed to adapt to novel conditions.

2.2.1. Coordination

Routinization can impair coordination of tightly interdependent tasks. Routinization delivers efficiency by creating specialized silos, where each unit focuses narrowly on executing its own set of explicit instructions. This specialization assumes that explicit knowledge captures all necessary information to reduce the incentive for informal information sharing and mutual adjustment (Nonaka, 1994; Puranam et al., 2012).

Even under expected conditions—if everything is perfectly standardized and the explicit knowledge is accurate—this organizational specialization can impair the execution of tightly interdependent tasks (Rawley, 2010). When tasks are highly interdependent, subtle misalignments or minor delays in one silo can cascade through the project. If teams adhering to pre-defined procedures do not expect to need to coordinate on nuance, these misalignments can slow down execution. Crucially, the efficiency gain derived from explicit procedures is predicated on not needing to coordinate in real time. In other words, an organizational design must assume the sufficiency of its knowledge to get efficiency from it. If agents were to invest time and cognitive capacity preparing for the potential need to actively coordinate, the efficiency gains intended by the routinization would be diminished. The organization maximizes efficiency precisely by assuming coordination is unnecessary.

Under this system, coordination problems arise during unexpected conditions or when not everything can be standardized. When the codified plan does not perfectly match the local reality, the organization should adapt, but an organization designed around its explicit knowledge naturally resists change. The silos created for efficiency become barriers to the flexibility needed to adapt to novel conditions (Feldman & Pentland, 2003). The specialized units, optimized for independent execution based on a plan, lack the established channels—or linking mechanisms (Mintzberg, 1979)—for communication and mutual adjustment required to respond collectively to the deviation. The organization, having prioritized specialized execution over communication, lacks the capacity to coordinate quickly when epistemic interdependence unexpectedly increases. Related to this point, Dutt and Lawrence (2022) find that increased breadth of activity generates coordination needs that can undermine performance. The organization, having optimized for a standardized past, becomes less malleable facing new conditions on the ground.

2.2.2. Crowding Out the Use of Tacit Knowledge

Crucially, the organizational design resulting from routinization crowds out the use of tacit knowledge accumulated alongside explicit knowledge. The process of codification creep does not necessarily eliminate the tacit knowledge gained from experience; rather, it prevents that tacit knowledge from being effectively deployed. Organizational structures and processes defined by explicit knowledge constrain individuals and teams from exercising judgment and deviating when needed. In effect, the organization becomes calcified around the explicit knowledge, now in effect a core rigidity (Leonard-Barton, 1992), limiting its ability to leverage tacit know-how required to coordinate complex tasks and adapt to novelty. Miller, Pentland, and Choi (2012) model this tension, demonstrating that while memory of "know-what" (as opposed to "know-how" or "know-who") facilitates efficiency in stable contexts, it obstructs efficiency gains when the organization encounters novel problems. This crowding out of tacit knowledge undermines the very efficiency gains sought from codification.

3. HYPOTHESIS DEVELOPMENT

In the preceding section, we developed the theory of codification creep, arguing that organizations seeking efficiency gains from experience engage in a cycle of codification, standardization, and routinization. This process creates organizational rigidity that hampers coordination and crowds out the use of tacit knowledge, potentially leading to a negative learning curve. To apply and, later, empirically test our theory of codification creep, we now turn to our empirical context: the global nuclear power plant construction industry.

We complement our quantitative analysis of the nuclear construction industry with qualitative insights to contextualize the theory of codification creep. We conduct 96 in-depth interviews with professionals in the nuclear energy industry—including civil engineers, project managers, executives, and regulators—to gather insights on historical practices. We also examine archival records of past projects including plant archives and regulatory filings. We incorporate selected anecdotes and insights from these interviews and archival records to illustrate the theoretical logic in a concrete way; they are not intended to serve as formal empirical evidence.

3.1. Nuclear Power Plant Construction

3.1.1. General Contractors and Construction Timelines

The commercial nuclear power plant construction industry provides a revealing context to examine codification creep. Since the mid-20th century, a handful of firms lead these construction projects, such as Bechtel Power Corporation (USA), Ontario Hydro (Canada), Japan Atomic Power Company (Japan), and Taylor Woodrow Construction (UK).[1] These firms, which we refer to as general contractors, have strong incentives to reduce on-site construction time.

General contractors in the nuclear power plant construction industry have been plagued by long construction timelines. Indeed, what is most striking is that nuclear power plant construction has not gotten faster over time. In fact, over most of the history and most parts of the world, plant construction has gotten slower over time. Figure 1 illustrates the general pattern.

— Insert Figure 1 Nuclear Power Plant Construction Durations—

Understanding Figure 1 requires some context on the composition of the data. Western general contractors dominated the industries first decades. US, UK, French, and German general contractors in the 1950s completed a plant in an average of 1,694 days; by the 1960s, it took 2,092 days; by the 1970s, it took 2,815 days; and by the 1980s, it took 2,909 days. In large part due to these ever longer timelines, Western general contractors abandoned plans for new plants. By the 1990s, construction durations miraculously fell to 1,861 days, but Western firms did not improve. Rather, new (and inexperienced) entrants from Canada, India, South Korea, and Japan began to lead most plant construction. These contractors, too, experienced increasing construction times, rising to 2,400 days in the 2000s. And although it again appears that projects got faster in 2010s, falling to 2,202 days, this drop in global averages came, once again, from new (inexperienced) entrants, now from China.[2]

3.1.2. Nuclear Power Plants

It is crucial to understand the specific scope of work for the general contractors we study, which

[1] In the industry, these firms are formally known as engineering, procurement, and construction (EPC) contractors.
[2] This pattern is consistent with theory by Posen and Chen (2013) that entrants may enjoy an advantage of newness in learning.

requires some context on nuclear power plants. A nuclear power plant generates electricity, of course, by using the heat from nuclear fission to boil water into steam, which then drives turbines to generate electricity. Figure 2 illustrates this process and the plant components relevant to this study.[3] The nuclear reactor is where the nuclear fission takes place. But the nuclear reactor is itself only a tiny component of what constitutes a nuclear power plant. From the perspective of the general contractors, and for the purpose of this study, we can think of the reactor as simply a black box where water goes in and steam comes out. The reactor itself is almost entirely pre-manufactured off-site and designed by a separate original equipment manufacturer (OEM) (e.g., Mitsubishi Heavy Industries, Siemens, Atomic Energy of Canada).

— Insert Figure 2 Nuclear Power Plant—

The general contractors in our study are responsible for the on-site civil engineering and systems integration surrounding the reactor, including: excavating, pouring foundations, erecting structures, installing piping, and connecting turbines. Building the plant requires little to none in the way of nuclear physics. To put it simply, general contractors deal with concrete and steel and rarely, if at all, with uranium.

3.2. Codification Creep and the Negative Learning Curve

The industry's interest in speeding up lengthy construction times led to an intentional strategy of standardization: general contractors sought to use the same reactor model across the construction of multiple nuclear power plants over time. The core of this strategy is the reactor model, a

[3] This illustration in Figure 2 and our description of the composition of a nuclear reactor are intentionally simplified for expositional purposes. We use the term *reactor* in this paper to refer to what the industry would consider a broader reactor system, which could include both the reactor along with several other components provided by the OEM that the industry would consider separate components, such as the reactor vessel and, for pressurized water reactors (PWR), the associated steam generators, as the reactor cannot function without them. For boiling water reactors (BWR), the steam generator function is integrated into the reactor vessel itself. Our simplified definition focuses on the interfaces (heat extraction, water intake, steam transfer) that create the interdependencies relevant to the civil engineering construction project, rather than the internal engineering specifics of the reactor system.

specific nuclear reactor with a fixed specification provided by the OEM. Empirically, we study experience accumulated at the level of a reactor model, i.e., how many times a general contractor builds a plant with a specific reactor. Conceptually, the reactor model represents the standardization around which explicit knowledge accumulates through codification and the organization progressively shapes itself through routinization.

The general contractors expected that replicating construction work around a standardized reactor model would yield faster construction.[4] A construction executive articulated this ethos: "the more [of a specific reactor model] we built [around], the better we hoped to get, the better we hoped the supply chain would get." In its public marketing materials, Westinghouse proclaims that construction around a AP1000 reactor will benefit from a "reduction in work hours to build" and a "reduction in component and construction materials" because it "set[s] the new industry standard" with technology for "modular construction" that can be replicated across multiple plant construction projects (Westinghouse Energy Company, 2025).[5] Similarly, the World Nuclear Association states that "standardisation of reactor designs … enables vendors and utilities to share and implement good practices and experience feedback in the construction and operation of standardized reactor fleets" (World Nuclear Association, 2008).

While some benefits of repeatedly constructing around standardized reactor models did materialize (e.g., in maintenance and operational reliability), the original motivating goal of faster construction was not achieved.[6] In fact, quite the opposite, as we will theoretically argue

[4] Regulators, too, favored repeated use of reactor models for the potential of faster construction but also anticipated gains elsewhere. A World Nuclear Association report (WNA) (2008) summed up the expected benefits: standardization allows organizations to draw on design and operating experience at all phases of a plant's life cycle—construction, commissioning, operation, decommissioning—thereby enhancing safety and performance. During construction, "each subsequent plant of the same design will benefit from the experience accumulated in the construction of previous plants."

[5] Recent interest around small modular reactor technology (SMRs) follows from the premise that they will allow repetition at scale to allow for learning that can reduce construction duration.

[6] Alexy, Poetz, Puranam, and Reitzig (2021) provide one explanation for why this belief in standardization persisted and continues to persist in 2025: if organizations myopically adopt organizational design to address immediate

and empirically show. We now apply our theory of codification creep to explain why.

A reactor model defines the standardized template around which general contractors replicate projects over time. In short, different reactor models heat water into steam at slightly different temperatures and pressures, creating specific interdependencies regarding how water enters and steam exits. This, in turn, affects the construction project because the infrastructure—the pipes, concrete, and steel—must be installed specifically to accommodate these interfaces. By standardizing the reactor model used across multiple projects, explicit knowledge could be accumulated from past projects and presumably applied later. The size of pipes and the number of gauges for one plant should be the same at the next plant if the same reactor model is used.

This standardization facilitated and incentivized codification of explicit knowledge by general contractors. General contractors use the first nuclear power plant built around a new reactor model, often called a first-of-a-kind or reference plant, to generate knowledge for use in subsequent plant construction based on the same reactor model. Companies formalized this approach by treating each completed plant as a knowledge repository for the next project. In an internal email about a new plant, one manager at a general contractor explained that the reference plant's as-built written documentation, updated with all lessons learned, would serve as the baseline for the next plant. The work for the next plant would be planned exactly according to the final specifications recorded from the previous plant—and so on.

Our study of detailed archival records reveals an exploding amount of meticulous detail in plant design accumulated from one plant to the next as general contractors learned more and more from past experience. We compare the construction plans for two projects by the same general contractor using the same Westinghouse Four-Loop reactor model: Cook-1 (the 8th

problems, the underlying logic of organizing can remain entrenched (in this context, a belief in the efficiency gains from standardization).

build, started in 1969) and Vogtle-1 (the 33rd build, started in 1976).[7] Despite the fundamental similarity of the projects, Vogtle-1 documentation exhibits a significantly higher density of information, annotations, and procedural notes. Expert interviews confirm that the increase in detail does not reflect any meaningful technological change between the two builds. Rather, it represents the accumulating codification of mundane details, such as specifying minor valves and gauges, that were certainly present in the Cook-1 plant but left undocumented.

To reap the seeming benefits from this wealth of explicit knowledge, general contractors then routinized around the explicit knowledge gained from constructing previous plants based on a specific reactor model. Our interviews reveal the many ways they adapted their organizational structures, processes, and coordination mechanisms. For instance, one firm pre-contracted precise work with teams of welders, pipefitters, and other specialists based on what they learned from their last project. The project manager explained that "once we locked in [the reactor model that needed a stainless-steel liner on its service building and containment building sumps], we selected team members and subcontractors based on the skills we already knew we would need. We were able to assign dedicated [metal fabrication and plumbing] teams so they could work in parallel." Furthermore, project processes were optimized to rely on documentation rather than active coordination, assuming standardization eliminated ambiguity. One civil engineer noted: "The schedule was gospel.…They [the general contractor] based it on the [realized] schedule from the last project…We were told that we needed to pour the concrete exactly by this date. The pipefitters would arrive the week after and needed the concrete ready."

Given the apparent codification, standardization, and routinization prevalent in the industry, our theory of codification creep implies a risk of organizational rigidity that impairs

[7] Appendix A details this case study of Cook-1 and Vogtle-1 and the archival research behind it.

both horizontal coordination and vertical coordination.

3.2.1. Horizontal Coordination

Large construction projects like building a nuclear power plant involve multiple specialized divisions (e.g., civil works, mechanical systems, safety) and subcontractors. These teams can become siloed due to routinization. If personnel assume that the documents capture all important information, they may communicate less about nuanced requirements. Several interviewees note that as designs become more detailed, consistent interpretation across thousands of pages of specifications proved challenging. Even minor discrepancies, often only apparent during later testing, necessitate rework causing delay. One manager remarked that when teams need to clarify specifications with one another, “everyone else might need to stop working.”

3.2.2. Vertical Coordination

Routinizing around explicit knowledge increases the costs of vertical coordination between the governed and the governing. When an organization is rigidly structured around a detailed codified plan, the locus of decision-making shifts upward: any deviation from that plan by the governed requires further consent and approval from those governing. Crucially, this incumbrance is often self-inflicted. With an abundance of explicit knowledge, a lower level of the organization tends to more precisely specify the workplan it pre-commits to higher levels, voluntarily narrowing its own scope of authorized action and limiting its own autonomy. In our context, the relationship between the general contractor and an industry regulator is best viewed through the lens of vertical coordination with the hierarchy of the broader project. While the regulator is legally a third party, in practice it functions similarly to internal governance, e.g., between a board of directors and a management team: the regulator largely enforces the parameters the general contractor has set for itself and maintains continuous oversight with inspectors physically co-located on-site.

From this perspective, the regulator acts not as the architect of delay, but as the strict enforcer of the firm's intended routines. Interviewed regulators reflected that the more detailed the plan submitted to regulators—a consequence of accumulated codification from past projects—the more frequently contractors triggered a formal review for minor deviations, even beneficial ones. The construction of the Vogtle Unit 3 plant reflects this dynamic. When laying the basemat foundation for the reactor, the contractor poured an alternate concrete mix that differed from the precise concrete specification it had filed with the regulator. The project was forced to wait for a formal review, but not because the regulator opposed the quality of the work: in fact, the regulator would find that the alternative concrete exceeded the required compressive strength and was, in fact, superior to what the contractor previously proposed. The regulator would have approved a plan with this alternate concrete, and as we discuss next, the regulator would have approved a plan without such specificity around the concrete. Instead, the firm willingly put itself in a position where it lacked the authority to improve its own process and needed the hierarchy to adjudicate an improvement that could otherwise been managed locally.

Given the pattern of standardization, codification, and subsequent routinization, we predict that accumulating more experience impairs efficient coordination. We hypothesize:

Hypothesis 1. Greater organizational experience building plants around a specific reactor model is associated with longer construction duration.

3.3. Adaptation to Unplanned Novelty

Perhaps the most damaging consequence of codification creep is the loss of flexibility in the face of *unplanned novelty*: unexpected events or changes that require the organization to improvise in real time. These events invalidate assumptions drawn from the explicit knowledge around which the organization was designed to operate. When the unexpected occurs, the efficient but rigid structure impairs both the horizontal and vertical coordination needed to adapt.[8]

A vivid example of this rigidity occurred during the construction of Vogtle Unit 3 in the United States. As workers laid down the massive basemat foundation for the reactor, they encountered downward deflection forming at its center, known as "dishing" or "cupping" (Gunderson, 2020). From a civil engineering standpoint, this deflection was a minor physical variance that could be addressed with on-site adjustments without posing a safety risk. However, the general contractor had surrendered its ability to use this tacit engineering judgment. The work now fell outside the highly specific tolerances the contractor itself had submitted for approval, paralyzing the organization: construction stopped for six months until the regulator could approve the alternate basemat specification (Southern Nuclear Operating Company, 2012).

This incident illustrates a core consequence of codification creep: the firm effectively removed its own discretion to manage the unexpected. As one engineer noted, the contractor had held itself to "overly stringent controls" by designing the finality of the outcome into the licensing process itself, rather than retaining the flexibility to adapt to "construction tolerances" that very regularly deviate from those "on paper." The delay was not imposed by a change in regulation, but by the firm's choice to forego flexibility allowed by the regulatory regime.[9]

Weather is a prime example of an unpredictable factor that tests the adaptability of the general contractors. Although planners account for typical seasonal patterns, unusually intense or

[8] While our argument focuses on structural rigidity, Gaba, Lee, Meyer-Doyle, and Zhao-Ding (2023) highlight a complementary behavioral mechanism: greater experience can engender overconfidence, making the organization less responsive to negative feedback.

[9] The U.S. regulatory regime (10 CFR Part 52) allows contractors to request plan approval without specifying all engineering details by filing "design acceptance criteria" (DAC). This approach creates a bounded space for future adaptation. In contrast, experienced contractors often take the legally unnecessary step of specifying all engineering details prior to construction through "final design approval" (FDA). This specificity self-imposes an obligation to file formal license amendments to seek time-consuming approval for deviation from the firm's own specifications.

unseasonal rain severely disrupts activities (Menches et al., 2008). Downpours disrupt work by damaging materials, flooding excavations, and creating hazardous conditions. Rain alters the properties of poured concrete during curing and may require additional drainage and pumping, prevent heavy equipment from accessing muddy areas, etc. And foundational work may have to be rescheduled or reinforced: one likely explanation for the “dishing” of Vogtle 3’s basemat is that the foundation pit contained more moisture than anticipated. Such knock-on effects force real-time resequencing of tasks (Hwang et al., 2017).

Unplanned novelty intensifies the negative impact of codification creep by exposing the organization’s diminished adaptability. Over-routinized firms struggle to adapt to unforeseen challenges, leading to larger performance shortfalls when surprises occur. We hypothesize:

> **Hypothesis 2.** The negative relationship between organizational experience and construction duration is augmented when the organization encounters unexpected weather (e.g., unusually heavy rainfall).

3.4. Disrupting Codification Creep with Planned Novelty

Unplanned novelty starkly reveals the downsides of codification creep. But counterintuitively, we argue that deliberately injecting novelty counteracts codification creep. We argue that *planned novelty*—intentional deviations introduced at a project’s outset—can serve as a countermeasure by compelling organizations to pre-emptively avoid rigid routinization and instead re-engage their tacit knowledge. By planned novelty, we refer to any significant and planned design change that the organization chooses to undertake in a new project, despite having a standard approach available.

When firms incorporate a novel element, then it becomes obvious ex ante that existing knowledge may not fully apply. Instead of tight routinization around what was recorded from the past, the organization becomes aware that it must instead leverage tacit knowledge by allowing for experimentation, open communication, and know-how. As we previously note, codification creep does not eliminate tacit knowledge gained from experience; it merely crowds out its use by creating rigid organizational structures. When planned novelty disrupts this process, the inherent benefits of accumulated tacit knowledge can re-emerge.

In our context, we focus on a consequential form of planned novelty: a general contractor deciding to implement a first-of-a-kind reactor containment building type. As the most critical and complex civil engineering in a plant, the containment building is the large, sealed structure that houses the reactor (see Figure 2). The International Atomic Energy Agency (IAEA) recognizes eight distinct containment building types, ranging from just concrete or just steel to reinforced concrete and steel.[10] While each containment building type can accommodate different reactor models, the building must be tailored to accommodate a reactor model's specific size and interfaces, i.e., the containment building and reactor model are interdependent. Even when building around the same reactor model, switching to a new containment building type introduces substantial novelty in construction methods. A contractor thus knows it cannot simply reuse the procedures documented from previous projects. This shifts the nature of knowledge application; as Stadler, Helfat, and Verona (2022) demonstrate, when units introduce new technologies, tacit expertise becomes a meaningful complement to organizational resources. This change compels a departure from routinization, constituting a form of strategic renewal, which Agarwal and Helfat (2009) argue allows an organization to alter its path dependence.

By making it clear ex ante that existing explicit knowledge will not be relevant, we argue that experienced contractors pre-empt the rigidity of codification creep. Instead, they can

[10] Appendix B.4 details the containment building types.

mobilize cross-functional teams to work through the new design's challenges together, relying on active judgment and coordination rather than just past templates (Walter et al., 2016). One interviewee described how introducing a new design "forces the engineers to actually talk to each other and think through implications," whereas with a familiar design they would retreat into following the established procedure for their own area of responsibility. Klingebiel and De Meyer (2013) highlight that when managers become aware of new uncertainty, they shift towards making deliberate and diligent decisions, rather than adhering to the plan.

We expect that firms with experience will perform better—by avoiding the routinization around explicit knowledge and, thereby, allowing them to leverage their tacit knowledge—when they deliberately include a novel element in the project.[11] We hypothesize:

> **Hypothesis 3.** The negative relationship between organizational experience and construction duration is attenuated or reversed by the introduction of planned novelty in the form of a novel containment building type.

4. METHODS

4.1. Nuclear Energy Industry

Our dataset consists of 598 nuclear power plant construction projects worldwide between 1951 and 2022. We combine comprehensive global data on all nuclear plant construction with meteorological and regulatory data from national and international agencies.[12]

[11] While the underlying motivation to choose an alternative novel containment building is presumably not about accelerating construction timelines, nor are we recommending that end as a reason why that choice should be made, there are other ways of fostering the use of tacit knowledge. We asked a global regulator to explain why it is that China seems to be building nuclear power plants much more quickly than they are built in Europe or America. The regulator explained that the relatively high speed of Chinese nuclear power plant builds can be explained by the "Chinese engineering approach," which he described as "trying different things and working by iteration." He compared this approach to "engineering in the Western sense as someone who makes a plan, sticks to the plan, and realizes it." Thus, the implication is not that Chinese firms are learning more or better but, rather, that they intentionally maintain flexibility to avoid codification creep.

[12] Appendix B.2 details this regulatory data collection. For instance, Canadian regulatory documents and guidelines are available from the Canadian Nuclear Safety Commission (CNSC).

Nuclear plant construction data comes from the Power Reactor Information System (PRIS), the authoritative database maintained by the IAEA (International Atomic Energy Agency, 2025). Regarded as the most reliable and extensive repository on nuclear power plants worldwide (Ahmad, 2021; Csereklyei et al., 2016; Lovering et al., 2016), PRIS tracks all manner of technical and operational information on each plant since the inception of nuclear energy, including critical variables such as construction start and end dates. PRIS includes the entire population of every nuclear power plant constructed, operational, or decommissioned globally, from the very first to the most recent. We exclude the few cases, less than five percent of the initial list, missing critical data, e.g., construction timelines, reactor specifications.

We combine the PRIS data with meteorological observations obtained from Open-Meteo, an open-source provider of global historical weather data dating back to 1940 (Zippengenig, 2023). By matching this with the geocoordinates of each site, we obtain daily weather data over six years, three years before and three years after construction start, at each site for a total of 1,387,849 observations of temperature, wind speed, precipitation, and daylight hours.

4.2. Measures

4.2.1. Dependent Variable

As our primary dependent variable, *Construction Duration* is the number of days the general contractor needed to complete construction. Specifically, we measure the days elapsed from the "first concrete day" to the criticality date.[13] First concrete day is when the first concrete pour subject to regulatory oversight takes place; the industry typically considers this the formal start

[13] To ensure the validity of our findings, we test our hypotheses against alternative definitions of this variable, including the total duration from first criticality date to the commercial operation date when the plant formally provides power to the grid; our main results remain robust to these measures. The duration between first concrete day and criticality date is the dominant component of the project timeline, accounting for 89.0% of the total duration from first concrete date to commercial operation.

of nuclear construction.[14] Criticality date marks the point when the reactor enters operational readiness, meaning it has achieved sustained nuclear fission.[15] These two milestones bookend the period when the general contractors in our study complete the vast majority of their construction work, making them a more meaningful measure for this study than alternative start or end dates.

Construction Duration is arguably the most important performance metric for all industry participants, not just the general contractors: nuclear power plants have extremely high fixed costs and relatively low variable operating costs, making the time it takes to build the plant a critical determinant of the project's overall economic viability. Even for a nuclear plant that goes on to operate for 60 years, the majority of its total lifetime cost, often exceeding 60 percent, is incurred during the construction phase due to capital expenditures, financing costs, and interest accumulated over the construction period (International Energy Agency, 2015). Prolonged construction timelines lead to escalating interest payments and increased capital costs, significantly inflating the total investment required.

4.2.2. Main Independent Variables

To measure organizational experience around a standardized project, *Reactor Model Experience* measures the cumulative number of times the general contractor has built a plant based on a specific reactor model as reported to the IAEA, taking a value of 1 for the first project.

To assess the impact of unplanned novelty, *Unexpectedly Heavy Rain* is the count of days during the first three years of construction that had a greater amount of rain, in millimeters, than

[14] We considered alternative start dates, like site preparation—which encompasses vague preliminary activities like tree clearing, road paving, and excavation—and regulatory approval, but these milestones lack broadly accepted definitions in the industry. Consequently, using them would introduce measurement error.

[15] We also consider alternative end dates such as grid connection date and the commercial operation date—the date the reactor formally begins providing power to the grid—but these reflect commission and utility firm behavior and have little to do with the general contractors. Nevertheless, the subsequent intervals of time that would be added are minor in comparison to the duration of *Construction Duration*, i.e., criticality to grid connection (2.5%) and grid connection to commercial operation (8.5%).

the same day of the year in any of the three years before the start of construction.

We operationalize planned novelty using a *Novel Containment Building* variable, a binary variable where 1 indicates that the organization is deploying a containment building type around that reactor model for the first time, and 0 otherwise, as reported to the IAEA.[16]

4.2.3. Control Variables

We include several control variables and fixed effects to account for factors known to influence the duration of plant construction. *Regulatory Burden* is the number of pages of nuclear regulation for the country of plant construction in the year construction was initiated, manually collected based on a detailed understanding of each country's regulatory system.[17] *Reactor Power Output*, measured in megawatts electric (MWe), reflects the net power output and implicitly, the size of the reactor. Construction of a plant for larger reactors typically requires more materials and labor. *Reactor Power Density*, measured in kilowatts per cubic meter (kW/m^3), is the average amount of power generated per unit volume of nuclear fuel within the reactor core. Higher-power-density reactors require advanced cooling systems and safety measures because they generate more heat within a smaller physical space. *Containment Building Complexity* reflects the complexity of the material composition and structural reinforcement of the containment building from least to most complex on a scale of 1 to 8.[18]

We control for the exogenous environmental conditions at each site: *Temperature* (mean temperature in degrees Celsius), *Temperature Variability* (standard deviation of temperature in degrees Celsius), *Precipitation* (mean precipitation in millimeters), *Wind Speed* (mean daily maximum wind speed in meters per second), and *Daylight* (mean daylight in seconds).

We control for *firm fixed effects* and *time fixed effects*. Given the lengthy study period (71

[16] Appendix B.4 details the different containment building types.
[17] Appendix B.2 details the construction of *Regulatory Burden*.
[18] Appendix B.4 details the construction of *Containment Building Complexity*.

years) and the multi-year construction times of reactors, we incorporate decade fixed effects to capture unobserved time-variant factors, e.g., macroeconomic conditions (Wheatley et al., 2017). *Country fixed effects* control for time-invariant factors specific to the country where the construction takes place, e.g., workforce, management culture. *Reactor manufacturer fixed effects* and *reactor technology fixed effects* account for differences across manufacturers and reactor technologies, e.g., boiling water reactors (BWR), pressurized water reactors (PWR).[19]

4.3. Descriptive Statistics

Table 1 presents summary statistics. *Construction Duration* averages about 6.6 years, with a standard deviation of roughly 3.2 years. Our key independent variables—*Reactor Model Experience*, *Unexpectedly Heavy Rain*, and *Novel Containment Building*—exhibit substantial variation. Table 2 reports pairwise correlations. While some variables correlate as expected (e.g., *Reactor Power Output* and *Construction Duration*), no correlations exceed accepted thresholds indicating problematic multicollinearity.

— Insert Table 1 Summary Statistics —

— Insert Table 2 Pairwise Correlations —

5. ANALYSIS AND RESULTS

Table 3 presents the results of our OLS regression analyses. Model 1 includes only the control variables to serve as a baseline for comparison. To test H1, Model 2 adds the main independent variable *Reactor Model Experience*. The coefficient for *Reactor Model Experience* is positive and significant ($\beta_1 = 18.53$, $p = 0.02$): each additional construction project using the same reactor model design is associated with an increase of 18.53 days of construction time. To put that into context, building the 20th plant, after having built 19 plants previously around the same reactor

[19] Appendix B.3 details the different nuclear reactor technologies.

model, takes about one year longer to complete than it took to build the first plant.

— Insert Table 3 Predictors of Construction Duration —

Model 3 tests H2 by including the interaction *Reactor Model Experience* × *Unexpectedly Heavy Rain*. The interaction term is positive ($\beta_3 = 0.21$, $p = 0.01$), indicating that unexpectedly heavy rain intensifies the negative effect of experience. On average, 100 days of unexpectedly heavy rain increases construction duration by 21 days for each prior plant built by the contractor.

Finally, Model 4 introduces the interaction *Reactor Model Experience* × *Novel Containment Building* to test H3. The negative and large interaction term ($\beta_5 = -95.91$, $p = 0.01$) supports H3 and suggests that planned novelty mitigates the negative effect of codification creep. The base effect of *Novel Containment Building* is positive, as one would directionally expect, but not statistically significant ($\beta_4 = -163.29$, $p = 0.39$). Interpreting the effect size alongside the *Reactor Model Experience* base effect ($\beta_1 = -67.51$, $p = 0.04$), a subsequent plant is 163.42 days (–67.51 + –95.91) faster to build than the previous plant if the contractor used a novel containment building on the focal project. Figure 3 illustrates these estimates.

— Insert Figure 3 Effect of Novel Containment Building—

5.1. Economic and Environmental Impact

The construction delays in the nuclear industry wasted more than just time: they carry substantial economic and environmental consequences. We estimate the excess economic costs and carbon emissions resulting from construction that extends beyond the planned seven-year industry benchmark. We find that each unit of experience is associated with an excess cost of nearly \$40 million and results in an additional 287,274 tonnes of excess CO_2 emissions, as nearly carbon-free nuclear power waits to come online and replace existing, carbon-intensive energy sources.[20]

[20] Appendix C details the analyses behind these estimates: Appendix C.1 describes the economic estimate of excess costs, and Appendix C.2 describes the environmental impact estimate of excess carbon emissions.

5.2. Supplemental Analyses

We conduct several supplemental analyses to assess the robustness of our findings with respect to alternative explanations. First, we test an alternative specification to explore construct validity independent of the specific operationalization of organizational experience and planned novelty.[21] Second, two sets of tests assess the possibility that increasing technical complexity over time, rather than codification creep, drives the observed delays.[22] For instance, reactor designs may have become more technically complex over time, or experienced contractors might select more technically complex projects. Third, we investigate whether changes in the regulatory or geopolitical environment confound our results. Nuclear regulations generally increasing over time, and they may incidentally track with organizational experience.[23] For instance, we test the sensitivity of our results to the Chernobyl disaster: while the disaster significantly increased construction duration in the industry, our main findings hold.

6. DISCUSSION

This study investigates a paradox of organizational experience: how the very processes designed to leverage past learning can ultimately degrade performance. Analyzing 598 nuclear power plant construction projects, we find a robust negative learning curve: general contractors become

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[21] Appendix D.1 details this analysis. We find results consistent with our main findings when using containment building experience to measure organizational experience and the introduction of a novel reactor model as the measure of planned novelty.

[22] Appendix D.2 details these analyses. Appendix D.2.1 presents subsample analyses across different reactor sizes to ensure the findings are not specific to a certain scale of technology. Appendix D.2.2 presents an overspecification test that introduces 36 additional technical control variables related to reactor design, nuclear fuel properties, and system characteristics. Our core findings remain robust across these tests.

[23] Appendix D.3 details these analyses. Appendix D.3.1 introduces an interaction term between *Reactor Model Experience* and the *Regulatory Burden* and finds no evidence that regulatory burden subsumes our main effect. Appendix D.3.2 test the sensitivity of our results to the Chernobyl disaster: we confirm that while the disaster significantly increased construction duration across the industry, it did not alter our overall finding relating experience to construction duration. Appendix D.3.3 controls for other major geopolitical events (e.g., OPEC embargo) and the cultural and geographic distance between the contractor and the construction site, ruling these out as alternative explanations. Appendix D.3.4 verifies that our results are not driven by countries with unique, state-controlled nuclear programs by excluding China, Russia, and Iran from the analysis. Across all these analyses, the main findings remain robust.

systematically slower as they accumulate experience building plants around a standardized reactor model. We introduce the concept of *codification creep* to explain this phenomenon. Organizations seeking efficiency codify their experience with standardized projects into explicit knowledge around which they routinize their structures. This routinization, while intended to speed up execution, crowds out the use of tacit knowledge, impairing coordination and adaptation to unplanned novelty. We now highlight generalizable implications of this theory for adjacent literatures on time compression diseconomies and transaction cost economics and end with practical implications for managing complex projects.

6.1. Time-Compression Diseconomies

Our findings contribute to research on time compression diseconomies (TCD) by explaining a new and alternative mechanism underlying this theory. TCD suggests that compressing the accumulation of assets—including knowledge—yields diminishing or negative returns (Dierickx & Cool, 1989; Lee & Park, 2024). Organizations often assume that explicit knowledge is more time-compressible than tacit knowledge. Consequently, they seek to accelerate future projects by rapidly codifying experience into explicit forms and standardizing future activities.

We propose that codification creep is a mechanism underlying TCD in learning contexts. To realize the benefits of explicit knowledge, organizations engage in routinization—adapting their structures and coordination mechanisms to align with that knowledge. By tailoring the organization to execute based on explicit records, firms crowd out the use of the flexible, tacit know-how required to adapt to inevitable variations (Benner & Tripsas, 2012; Davis & Aggarwal, 2020). The effort to speed up projects created rigidity that ultimately slowed them down. By compressing learning time, diseconomies later manifest as execution delays.

Our findings offer a prescription to mitigate these diseconomies. Prior work proposes that timing and pacing of experience matter (e.g., "too much, too fast") (Hawk & Pacheco-de-Almeida, 2018; Pacheco-de-Almeida et al., 2015). We demonstrate that deliberately injecting planned novelty can disrupt the cycle of codification creep, benefiting the experienced firms the most. Thus, it is not experience per se that hinders performance but, rather, the organizational rigidity that results from attempting to leverage that experience through explicit means (Wang et al., 2020). Proactively timing novelty can avert the liability of accumulated experience.

6.2. Transaction Cost Economics

Second, our study contributes to work on transaction cost economics (TCE) by demonstrating a limitation of codification for governance. The classical TCE view suggests that when transactions can be clearly specified and outcomes verified, firms should favor market-based contracts over internal organization to minimize transaction costs (Williamson, 1985). However, this perspective overlooks a critical limitation: a written contract, mechanically, can only reflect explicit knowledge. It cannot capture tacit know-how or unforeseeable contingencies (Argyres et al., 2020; Silverman, 1999). When organizations routinize their operations around an explicit contract, they implicitly prioritize specialized execution over adaptability.

Our findings caution that reliance on explicit knowledge can generate significant ex post rigidity. When unexpected novelty occurs, the organizational rigidity resulting from routinization impairs the coordination needed to adapt. The silos created for efficiency become barriers to flexibility. As a result, what TCE might label a low-uncertainty transaction can still incur high ex post costs if managed through inflexible contracts (Argyres et al., 2019; Lumineau & Malhotra, 2011). The Vogtle-3 project described in Section 3.3 illustrates this: a halt to work because the issue fell outside a "contract" between the general contractor and the regulator.

These findings suggest that the capacity to adapt to novelty depends on governance choices. Just because a transaction can be specified explicitly does not mean it should be managed through a contract. To preserve the use of tacit knowledge, firms may prefer lightly specified contracts or, in the extreme, vertical integration, which facilitates the use and transfer of tacit knowledge more effectively than arm's-length transactions.

6.3. Practical Implications

We highlight two key implications for the management of complex, standardized projects: the risks of over-specification in contracting and the potential of hybrid governance models.

First, dominant practices in the nuclear industry may inadvertently exacerbate codification creep.[24] The increasingly detailed contracts, checklists, and manuals intensify the routinization. Managers and policymakers in nuclear should consider limiting what they decide to codify and restrain the routinization that follows. Critics might worry that reducing codification invites safety risks; however, we find no evidence that accumulated experience by general contractors improves safety. We note with some irony that Chernobyl Unit 4, the site of the industry's most catastrophic failure, was the 13th plant constructed around the RBMK reactor model. Conversely, the first-of-a-kind plant with the RMBK reactor, Leningrad Unit 1, operated without incident until its scheduled retirement in 2018.

Second, the tension between standardization and adaptation can be alleviated through novel governance models. Emerging approaches to Small Modular Reactor (SMR) deployment utilize platform-based models (Adner & Kapoor, 2010). By externalizing tacit-intensive tasks to partners specializing in local adaptation, the platform approach reduces the opportunity and need for a global contractor to centrally codify every detail. A hybrid governance solution (Kretschmer et al., 2022) may be able to balance consistency across projects with local adaptability.

[24] For instance, our findings suggest that providing detailed plans to regulators creates vertical coordination constraints. We advise a shift toward more flexible governance frameworks already allowed by regulators, which allow for the integration of real-time, tacit judgment during construction.

7. REFERENCES

Adner, R., & Kapoor, R. (2010). Value creation in innovation ecosystems: How the structure of technological interdependence affects firm performance in new technology generations. *Strategic Management Journal*, *31*(3), 306–333.

Agarwal, R., & Helfat, C. E. (2009). Strategic renewal of organizations. *Organization Science*, *20*(2), 281–293.

Aggarwal, V. A., Posen, H. E., & Workiewicz, M. (2017). Adaptive capacity to technological change: A microfoundational approach. *Strategic Management Journal*, *38*(6), 1212–1231.

Ahmad, A. (2021). Increase in frequency of nuclear power outages due to changing climate. *Nature Energy*, *6*(7), 755–762.

Alexy, O., Poetz, K., Puranam, P., & Reitzig, M. (2021). Adaptation or persistence? Emergence and revision of organization designs in new ventures. *Organization Science*, *32*(6), 1439–1472.

Argote, L. (1999). *Organizational Learning: Creating, Retaining and Transferring Knowledge*. Kluwer Academic Publishers, Norwell, MA.

Argote, L., & Epple, D. (1990). Learning curves in manufacturing. *Science*, *247*(4945), 920–924.

Argote, L., Lee, S., & Park, J. (2021). Organizational learning processes and outcomes: Major findings and future research directions. *Management Science*, *67*(9), 5399–5429.

Argyres, N., Bercovitz, J., & Zanarone, G. (2020). The role of relationship scope in sustaining relational contracts in interfirm networks. *Strategic Management Journal*, *41*(2), 222–245.

Argyres, N., Mahoney, J. T., & Nickerson, J. (2019). Strategic responses to shocks: Comparative adjustment costs, transaction costs, and opportunity costs. *Strategic Management Journal*, *40*(3), 357–376.

Arrow, K. J. (1962). The economic implications of learning by doing. *Review of Economic Studies*, *29*(3), 155–173.

Balasubramanian, N., & Lee, J. (2008). Firm age and innovation. *Industrial and Corporate Change*, *17*(5), 1019–1047.

Baldwin, C. Y., & Clark, K. B. (2000). *Design Rules, Volume 1: The Power of Modularity*. MIT Press, Cambridge, MA.

Benner, M. J., & Tripsas, M. (2012). The influence of prior industry affiliation on framing in nascent industries: The evolution of digital cameras. *Strategic Management Journal*, *33*(3), 277–302.

Cattani, G., Dunbar, R. L. M., & Shapira, Z. (2013). Value creation and knowledge loss: The case of Cremonese stringed instruments. *Organization Science*, *24*(3), 813–830.

Csereklyei, Z., Rubio-Varas, M. M., & Stern, D. I. (2016). Energy and economic growth: The stylized facts. *Energy Journal*, *37*(2), 223–256.

Darr, E. D., Argote, L., & Epple, D. (1995). The acquisition, transfer, and depreciation of knowledge in service organizations: Productivity in franchises. *Management Science*, *41*(11), 1750–1762.

Davis, J. P., & Aggarwal, V. A. (2020). Knowledge mobilization in the face of imitation: Microfoundations of knowledge aggregation and firm-level innovation. *Strategic Management Journal*, *41*(11), 1983–2014.

Dierickx, I., & Cool, K. (1989). Asset stock accumulation and sustainability of competitive

advantage. *Management Science*, *35*(12), 1504–1511.
Dutt, N., & Lawrence, M. (2022). Learning to manage breadth: Experience as repetition and adaptation. *Organization Science*, *33*(4), 1300–1318.
Dyer, J. H., & Nobeoka, K. (2000). Creating and managing a high-performance knowledge-sharing network: The Toyota case. *Strategic Management Journal*, *21*(3), 345–367.
Eash-Gates, P., Klemun, M. M., Kavlak, G., McNerney, J., Buongiorno, J., & Trancik, J. E. (2020). Sources of cost overrun in nuclear power plant construction call for a new approach to engineering design. *Joule*, *4*(11), 2348–2373.
Eckardt, R., Skaggs, B. C., & Youndt, M. (2014). Turnover and knowledge loss: An examination of the differential impact of production manager and worker turnover in service and manufacturing firms. *Journal of Management Studies*, *51*(7), 1025–1057.
Epple, D., Argote, L., & Murphy, K. (1996). An empirical investigation of the microstructure of knowledge acquisition and transfer through learning by doing. *Operations Research*, *44*(1), 77–86.
Feldman, M. S., & Pentland, B. T. (2003). Reconceptualizing organizational routines as a source of flexibility and change. *Administrative Science Quarterly*, *48*(1), 94–118.
Gaba, V., Lee, S., Meyer-Doyle, P., & Zhao-Ding, A. (2023). Prior experience of managers and maladaptive responses to performance feedback: Evidence from mutual funds. *Organization Science*, *34*(2), 894–915.
Galbraith, J. (1973). *Designing Complex Organizations*. Addison-Wesley, Boston, MA.
Gunderson, A. (2020). *Declaration of Arnold Gundersen to support the petition for leave to intervene and request for hearing by the Blue Ridge Environmental Defense League regarding Southern Nuclear Operating Company's request for license amendment, Vogtle Unit 3 auxiliary building wall 11 seismic gap requirements (LAR-20-001)*. Nuclear Regulatory Commission, Before the Secretary, Washington, DC.
Hadjimichael, D., Pyrko, I., & Tsoukas, H. (2024). Beyond tacit knowledge: How Michael Polanyi's theory of knowledge illuminates theory development in organizational research. *Academy of Management Review*, *49*(4), 919–934.
Hanisch, M., Graf-Vlachy, L., Haeussler, C., König, A., & Cho, T. S. (2025). Kindred spirits: Cognitive frame similarity and good faith provisions in strategic alliance contracts. *Strategic Management Journal*, *46*(2), 436–469.
Hannan, M. T., & Freeman, J. (1984). Structural inertia and organizational change. *American Sociological Review*, *49*(2), 149–164.
Hawk, A., & Pacheco-de-Almeida, G. (2018). Time compression (dis)economies: An empirical analysis. *Strategic Management Journal*, *39*(9), 2489–2516.
Heimeriks, K. H., Bingham, C. B., & Laamanen, T. (2015). Unveiling the temporally contingent role of codification in alliance success. *Strategic Management Journal*, *36*(3), 462–473.
Heimeriks, K. H., Schijven, M., & Gates, S. (2012). Manifestations of higher-order routines: The underlying mechanisms of deliberate learning in the context of postacquisition integration. *Academy of Management Journal*, *55*(3), 703–726.
Helfat, C. E., & Winter, S. G. (2011). Untangling dynamic and operational capabilities: Strategy for the (n)ever-changing world. *Strategic Management Journal*, *32*(11), 1243–1250.
Henderson, R., & Clark, K. B. (1990). Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly*, *35*(1), 9–30.
Hwang, B.-G., Zhu, L., & Ming, J. T. T. (2017). Factors affecting productivity in green building

construction projects: The case of Singapore. *Journal of Management in Engineering*, *33*(3).
International Atomic Energy Agency. (2025). *Power Reactor Information System (PRIS)*. https://pris.iaea.org/pris/.
International Energy Agency. (2015). *Projected Costs of Generating Electricity 2015*. https://www.iea.org/reports/projected-costs-of-generating-electricity-2015.
Kale, P., & Singh, H. (2007). Building firm capabilities through learning: The role of the alliance learning process in alliance capability and firm-level alliance success. *Strategic Management Journal*, *28*(10), 981–1000.
Keller, A., Lumineau, F., Mellewigt, T., & Ariño, A. (2021). Alliance governance mechanisms in the face of disruption. *Organization Science*, *32*(6), 1542–1570.
Klingebiel, R., & De Meyer, A. (2013). Becoming aware of the unknown: Decision making during the implementation of a strategic initiative. *Organization Science*, *24*(1), 133–153.
Kretschmer, T., Leiponen, A., Schilling, M., & Vasudeva, G. (2022). Platform ecosystems as meta-organizations: Implications for platform strategies. *Strategic Management Journal*, *43*(3), 405–424.
Lee, S., & Park, J. (2024). Giving up learning from failures? An examination of learning from one's own failures in the context of heart surgeons. *Strategic Management Journal*, *45*(10), 2063–2094.
Leiblein, M. J., Chen, J. S., & Posen, H. E. (2023). Uncertain learning curves: Implications for first-mover advantage and knowledge spillovers. *Academy of Management Review*, *48*(1), 123–148.
Leonard-Barton, D. (1992). Core capabilities and core rigidities: A paradox in managing new product development. *Strategic Management Journal*, *13*(S1), 111–125.
Leonard-Barton, D. (1995). *Wellsprings of Knowledge: Building and Sustaining the Sources of Innovation*. Harvard Business School Press, Boston, MA.
Levitt, B., & March, J. G. (1988). Organizational learning. *Annual Review of Sociology*, *14*(1), 319–338.
Lovering, J. R., Yip, A., & Nordhaus, T. (2016). Historical construction costs of global nuclear power reactors. *Energy Policy*, *91*, 371–382.
Lumineau, F., & Malhotra, D. (2011). Shadow of the contract: How contract structure shapes interfirm dispute resolution. *Strategic Management Journal*, *32*(5), 532–555.
March, J. G. (1991). Exploration and exploitation in organizational learning. *Organization Science*, *2*(1), 71–87.
March, J. G., & Simon, H. A. (1958). *Organizations*. John Wiley & Sons, New York, NY.
Menches, C. L., Hanna, A. S., Nordheim, E. V., & Russell, J. S. (2008). Impact of pre-construction planning and project characteristics on performance in the US electrical construction industry. *Construction Management and Economics*, *26*(8), 855–869.
Miller, G. A., Galanter, E., & Pribram, K. H. (1960). *Plans and the Structure of Behavior*. Henry Holt and Co., New York, NY.
Miller, K. D., Pentland, B. T., & Choi, S. (2012). Dynamics of performing and remembering organizational routines. *Journal of Management Studies*, *49*(8), 1536–1558.
Mintzberg, H. (1979). *The Structuring of Organizations*. Prentice Hall, Englewood Cliffs, NJ.
Nelson, R. R., & Winter, S. G. (1982). *An Evolutionary Theory of Economic Change*. Belknap Press of Harvard University Press, Boston, MA.
Nonaka, I. (1994). A dynamic theory of organizational knowledge creation. *Organization*

Science, *5*(1), 14–37.
Nonaka, I., & Takeuchi, H. (1995). *The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation*. Oxford University Press, New York, NY.
Pacheco-de-Almeida, G., Hawk, A., & Yeung, B. (2015). The right speed and its value. *Strategic Management Journal*, *36*(2), 159–176.
Polanyi, M. (1966). *The Tacit Dimension*. Doubleday, Garden City, NY.
Posen, H. E., & Chen, J. S. (2013). An advantage of newness: Vicarious learning despite limited absorptive capacity. *Organization Science*, *24*(6), 1701–1716.
Puranam, P., Raveendran, M., & Knudsen, T. (2012). Organization design: The epistemic interdependence perspective. *Academy of Management Review*, *37*(3), 419–440.
Raveendran, M., Silvestri, L., & Gulati, R. (2020). The role of interdependence in the microfoundations of organization design: Task, goal, and knowledge interdependence. *Academy of Management Annals*, *14*(2), 828–868.
Rawley, E. (2010). Diversification, coordination costs, and organizational rigidity: Evidence from microdata. *Strategic Management Journal*, *31*(8), 873–891.
Sanchez, R., & Mahoney, J. T. (1996). Modularity, flexibility, and knowledge management in product and organization design. *Strategic Management Journal*, *17*(S2), 63–76.
Silverman, B. S. (1999). Technological resources and the direction of corporate diversification: Toward an integration of the resource-based view and transaction cost economics. *Management Science*, *45*(8), 1109–1124.
Southern Nuclear Operating Company. (2012). *Re: Vogtle Electric Generating Plant Units 3 and 4. Response to Request for Additional Information Letter No. 02 Related to License Amendment Request (LAR) 12-003 (Report No. ND-12-1503)*.
Thompson, J. (1967). *Organizations in Action: Social Science Bases of Administrative Theory*. McGraw-Hill, New York, NY.
Thompson, P. (2007). How much did the liberty shipbuilders forget? *Management Science*, *53*(6), 908–918.
Walsh, J. P., & Ungson, G. R. (1991). Organizational memory. *Academy of Management Review*, *16*(1), 57–91.
Walter, J., Lechner, C., & Kellermanns, F. W. (2016). Learning activities, exploration, and the performance of strategic initiatives. *Journal of Management*, *42*(3), 769–802.
Wang, T., Aggarwal, V. A., & Wu, B. (2020). Capability interactions and adaptation to demand-side change. *Strategic Management Journal*, *41*(9), 1595–1627.
Westinghouse Energy Company. (2025). *AP1000 Pressurized Water Reactor*. https://westinghousenuclear.com/energy-systems/ap1000-pwr/.
Williamson, O. E. (1985). *The Economic Institutions of Capitalism*. Free Press, New York, NY.
Winter, S. G., & Szulanski, G. (2001). Replication as strategy. *Organization Science*, *12*(6), 730–743.
World Nuclear Association. (2008). *International Standardization of Nuclear Reactor Designs*. https://world-nuclear.org/our-association/publications/working-group-reports/cordel-standardization-of-reactor-designs.
Wright, T. P. (1936). Factors affecting the cost of airplanes. *Journal of the Aeronautical Sciences*, *3*(4), 122–128.
Zander, U., & Kogut, B. (1995). Knowledge and the speed of the transfer and imitation of organizational capabilities: An empirical test. *Organization Science*, *6*(1), 76–92.
Zippengenig, P. (2023). *Climate Change API*. Open-Meteo.

https://openmeteo.substack.com/p/climate-change-api
Zollo, M., & Singh, H. (2004). Deliberate learning in corporate acquisitions: Post-acquisition strategies and integration capability in U.S. bank mergers. *Strategic Management Journal*, *25*(13), 1233–1256.
Zollo, M., & Winter, S. G. (2002). Deliberate learning and the evolution of dynamic capabilities. *Organization Science*, *13*(3), 339–351.

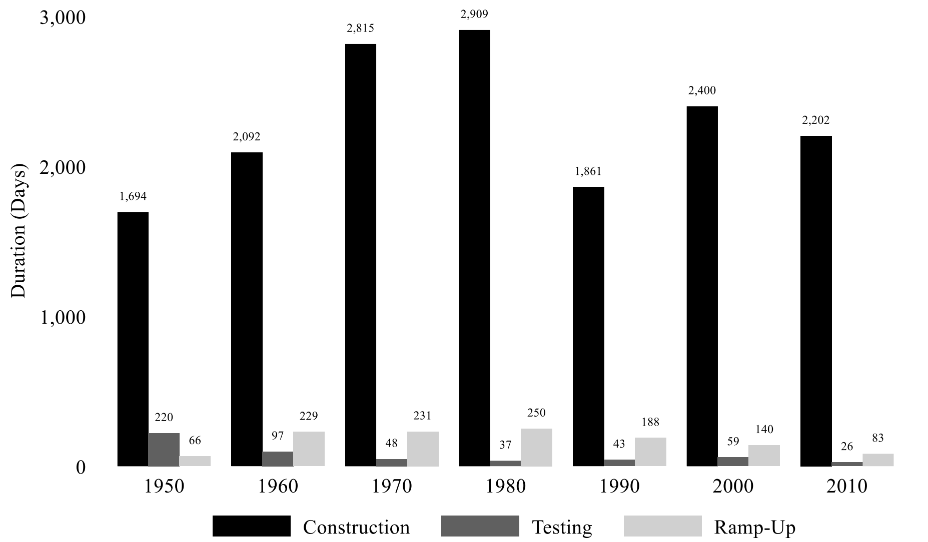


FIGURE 1 NUCLEAR POWER PLANT CONSTRUCTION DURATIONS Based on IAEA data. In additon to construction duration, we report testing duration (from first criticality to grid connection) and ramp-up duration (from grid connection to commercial operation, i.e., supply of electrical power to consumers).

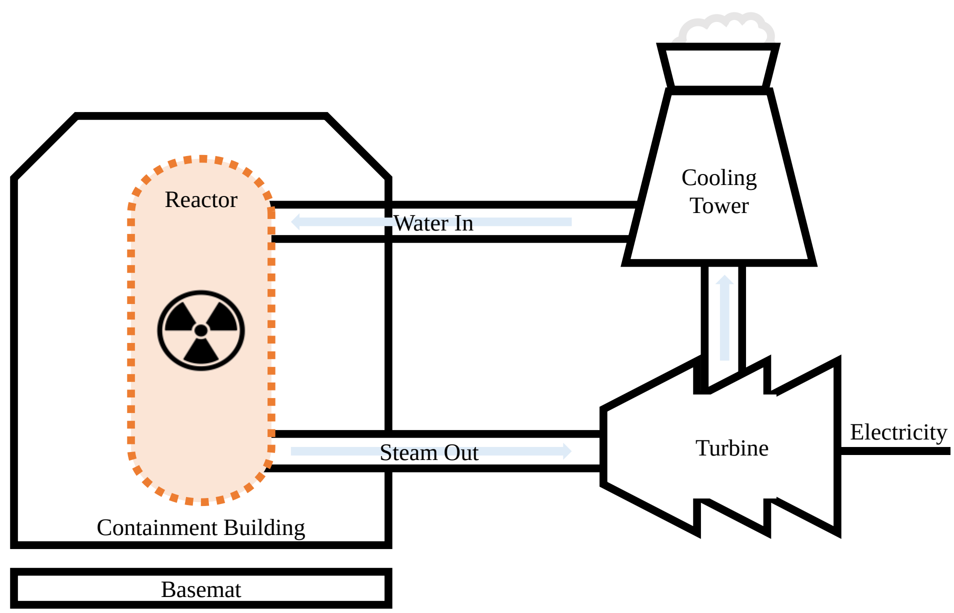


FIGURE 2 NUCLEAR POWER PLANT Basic components of a nuclear power plant: the *Reactor* generates heat to convert water into steam, which travels to the *Turbine* to generate electricity. The general contractor is responsible for the pipes for water and steam, *Containment Building*, and *Basemat*, whereas the reactor is provided by an OEM. For simplicity, the electric generator and condenser are not depicted. In the case of Pressurized Water Reactors (PWR), the component labeled *Reactor* encompasses the reactor vessel, pressurizer, and steam generators.

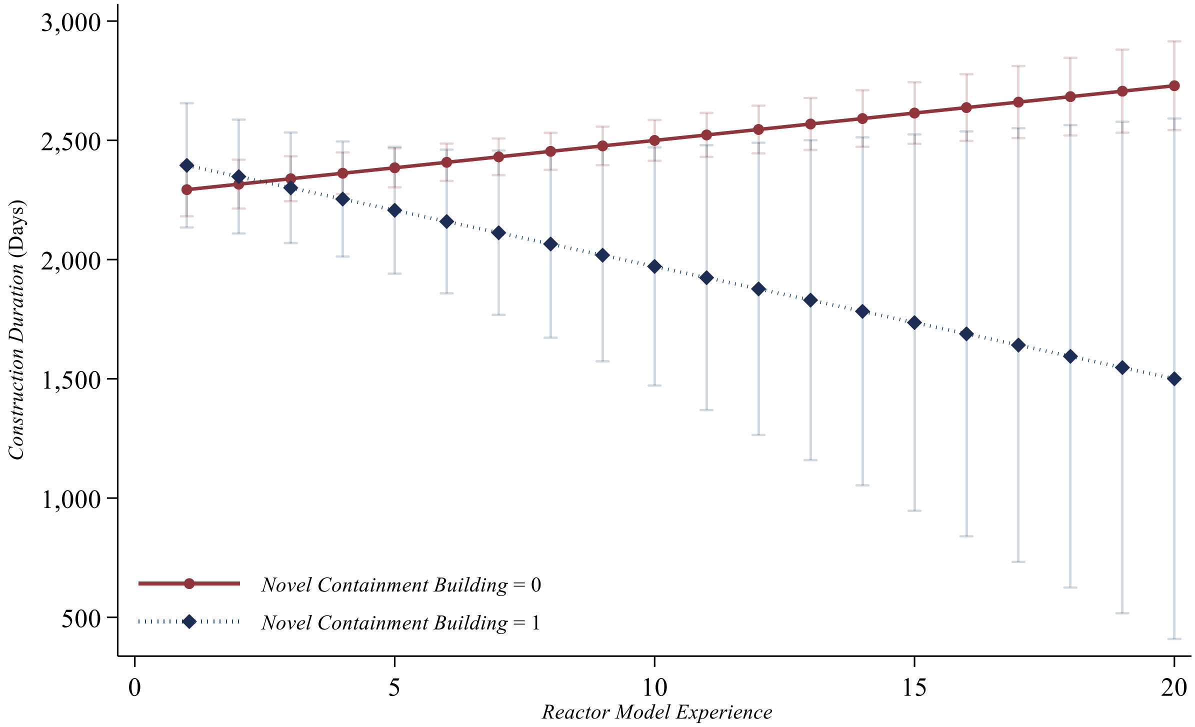


FIGURE 3 EFFECT OF NOVEL CONTAINMENT BUILDING Illustration of the marginal effect of *Reactor Model Experience* on *Construction Duration* by whether the project involves a *Novel Containment Building*. Error bars indicate 95% confidence intervals.

TABLE 1 SUMMARY STATISTICS 598 plant-level observations.

Variable	Mean	Std. Dev.	Minimum	Maximum
Construction Duration	2,410.39	1,188.11	366.00	9,763.00
Reactor Model Experience	6.61	6.39	1	34
Unexpectedly Heavy Rain	386.16	89.26	0	573
Novel Containment Building	0.11	0.31	0	1
Regulatory Burden	651.83	696.62	20.00	4,500.00
Reactor Power Output	758.70	373.15	5	1,660
Reactor Power Density	32.87	45.77	1.08	1,091.00
Containment Building Complexity	4.47	1.91	1	8
Temperature	12.19	5.85	–11.66	27.72
Temperature Variability	7.86	2.54	1.16	17.14
Precipitation	2.84	1.29	0.29	7.86
Wind Speed	19.98	4.92	8.71	35.17
Daylight	44,023.54	265.60	43,650.09	45,683.56

TABLE 2 PAIRWISE CORRELATIONS

	Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1)	Construction Duration	1.000						
(2)	Reactor Model Experience	0.280	1.000					
(3)	Unexpectedly Heavy Rain	0.013	0.118	1.000				
(4)	Novel Containment Building	–0.124	–0.222	–0.011	1.000			
(5)	Regulatory Burden	0.159	0.152	0.215	–0.116	1.000		
(6)	Reactor Power Output	0.252	0.235	0.138	–0.239	0.396	1.000	
(7)	Reactor Power Density	0.027	–0.032	–0.140	0.084	0.073	0.037	1.000
(8)	Containment Building Complexity	0.098	0.034	0.085	0.060	0.112	0.317	0.034
(9)	Temperature	0.029	0.097	0.381	0.020	0.211	0.128	–0.037
(10)	Temperature Variability	0.016	–0.050	–0.088	–0.033	0.113	0.049	0.063
(11)	Precipitation	–0.233	–0.035	0.406	–0.004	0.020	0.116	–0.051
(12)	Wind Speed	–0.129	0.060	0.082	0.030	0.002	0.028	–0.084
(13)	Daylight	0.024	–0.063	–0.311	–0.022	–0.118	–0.233	0.010

		(8)	(9)	(10)	(11)	(12)	(13)
(8)	Containment Building Complexity	1.000					
(9)	Temperature	0.290	1.000				
(10)	Temperature Variability	–0.171	–0.594	1.000			
(11)	Precipitation	0.020	0.394	–0.226	1.000		
(12)	Wind Speed	–0.117	–0.011	–0.165	0.253	1.000	
(13)	Daylight	–0.193	–0.773	0.259	–0.426	–0.039	1.000

TABLE 3 PREDICTORS OF CONSTRUCTION DURATION Ordinary least squares (OLS) estimation. Robust standard errors are clustered at the firm level. *p*-values are shown in parentheses.

Construction Duration	(4.1)	(4.2)	(4.3)	(4.4)
Reactor Model Experience		18.53	–67.95	–67.51
		(0.02)	(0.04)	(0.04)
Unexpectedly Heavy Rain			–0.13	–0.13
			(0.85)	(0.86)
Reactor Model Experience × Unexpectedly Heavy Rain			0.21	0.21
			(0.01)	(0.01)
Novel Containment Building				163.29
				(0.39)
Reactor Model Experience × Novel Containment Building				–95.91
				(0.01)
Regulatory Burden	1.55	1.58	1.62	1.58
	(0.00)	(0.00)	(0.00)	(0.00)
Reactor Power Output	1.59	1.59	1.59	1.58
	(0.00)	(0.00)	(0.00)	(0.00)
Reactor Power Density	0.73	0.68	0.79	0.78
	(0.51)	(0.54)	(0.48)	(0.49)
Containment Building Complexity	–25.01	–18.92	–15.40	–14.53
	(0.41)	(0.53)	(0.61)	(0.63)
Temperature	–20.78	–29.30	–28.69	–32.64
	(0.38)	(0.22)	(0.23)	(0.17)
Temperature Variability	–14.12	–30.91	–25.12	–31.69
	(0.72)	(0.43)	(0.52)	(0.42)
Precipitation	–66.97	–64.18	–83.16	–77.15
	(0.20)	(0.21)	(0.11)	(0.14)
Wind Speed	–15.52	–18.02	–17.03	–17.48
	(0.14)	(0.09)	(0.11)	(0.10)
Daylight	–0.02	–0.03	–0.08	–0.11
	(0.95)	(0.92)	(0.83)	(0.75)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Reactor Manufacturer FE	Yes	Yes	Yes	Yes
Reactor Technology FE	Yes	Yes	Yes	Yes
Observations	598	598	598	598
AIC	9,866.4	9,861.7	9,852.5	9,846.8
R^2	0.571	0.575	0.585	0.591

APPENDIX

A. CASE STUDY: COOK-1 VS. VOGTLE-1

In this section, we document a comparative case study of two projects in our sample, COOK-1 and VOGTLE-1, to illustrate and provide anecdotal evidence of our theory of codification creep. Unit 1 of the Donald C. Cook Nuclear Plant, which we refer to as COOK-1, started construction on March 25, 1969. Unit 1 of the Alvin W. Vogtle Electric Generating Plant (Plant Vogtle), which we refer to as VOGTLE-1, started construction on August 1, 1976.

We selected these two projects because they are similar on many dimensions but built at different times with a differently experienced general contractor. They are both based on the same reactor model, i.e., Westinghouse Four-Loop (W4LP) reactors, both of course with the same pressurized water reactor (PWR) technology. Both were built in the United States under similar weather conditions. Both reactors are of comparable size, utilize the same number of steam generators, include the same number of fuel assemblies, and rely on the same 18-month offline refueling frequency. Appendix Table I provides a detailed comparison of these projects.

— Insert Appendix Table I Cook-1 vs. Vogtle-1 Comparison —

However, and most critically, Cook-1 was the 8th W4LP reactor built and Vogtle-1 was the 33rd W4LP reactor built. Seven years and 25 reactors worth of experience separate the two projects. Consistent with our theory, the construction of the older COOK-1 took 5.8 years while the newer VOGTLE-1 lasted 10.6 years.

A.1. Comparison of Archival Data on Construction Plans

We examine the construction plans for these two projects to uncover evidence illustrating the codification creep in action. Through extensive archival research, we were able to obtain the original design plans and filings for these two projects. The set of documents total many thousands of pages long for each project. By comparing these plans across parallel aspects of the projects, it becomes abundantly clear that there was significantly more codification for VOGTLE-1 than there was for COOK-1. This observation is striking, simply because they are nearly identical projects in their eventual result, except the general contractor had significantly more experience when constructing VOGTLE-1 than when it constructed COOK-1.

Here, we provide selected excepts from the projects illustrating parallel aspects of the two projects for the reader to examine for themselves. We intentionally omit any technical commentary here as it is not necessary for seeing the pattern: COOK-1 and VOGTLE-1 are nearly identical projects, but there is significantly more detail recorded in the plans for VOGTLE-1 than COOK-1. Appendix Figure I shows the plans for the reactor vessel for COOK-1 and VOGTLE-1, respectively. Appendix Figure II shows the plans for their coolant systems. Appendix Figure III shows the plans for their steam generators. Appendix Figure IV and Appendix Figure V show the plans for the pressurizer of COOK-1 and VOGTLE-1, respectively.

— Insert Appendix Figure I Reactor Vessel —

— Insert Appendix Figure II Coolant System —

— Insert Appendix Figure III Steam Generator —

— Insert Appendix Figure IV Pressurizer: Cook-1 —

— Insert Appendix Figure V Pressurizer: Vogtle-1 —

The starkest difference between the plans is the sheer density of information, annotations, and explicit instructions present in the Vogtle-1 diagrams compared to the relatively sparse Cook-1 diagrams. This difference is driven by the explicit codification of details that were previously left to tacit understanding. For example, Note 8 in the Vogtle-1 Reactor Vessel diagram (Appendix Figure I) explicitly states that Westinghouse furnishes the reactor coolant loop piping. While Westinghouse almost certainly provided this piping for Cook-1 as well (as is standard practice by nearly all reactor OEMs), it was not explicitly documented in the earlier plans. Similarly, Note 3 in the Vogtle-1 Coolant System diagram (Appendix Figure II) meticulously details supplier responsibilities for standard equipment and valves. This trend toward documenting mundane information illustrates how explicit knowledge accumulated with experience, even absent significant changes to the underlying reactor technology.

A.2. Expert Analysis

We interviewed several industry experts with knowledge of these projects to better understand the pattern apparent in a comparison of the plans for these two projects. These interviews are further described in Appendix B.1. These informants indicated us that there were not any significant differences in the technology for the two projects that would require significantly more detailed plans for one project vs. another. For instance, one engineer commented: "The specific technical differences [between COOK-1 and VOGTLE-1] are not likely super significant." The same engineer added, "Even though they are both four-loop PWR designs of approximately the same vintage, [the detail of the plans] are still 100 years apart." He then drew an analogy to a similar situation with another pair of projects: "While the older Bruce B [Bruce Nuclear Generating Station Plant B] and the newer DNGS [Darlington Nuclear Generating Station] [two Canadian nuclear plant projects] both output similar power and are both based on the two-loop CANDU reactor [a specific reactor model], the designs and instrumentation are very different. Darlington's documentation is also similar to the technical level of Vogtle, while Bruce's looks similar to Cook."

The difference in detail and complexity of these design drawings, along with the assessment of industry experts, reflects ever growing codification as general contractors gained experience with a reactor model. While this particular case study is by no means conclusive evidence of our theory, the illustration strengthens our confidence in the existence of the underlying mechanism of increasing codification with greater experience.

B. EMPIRICAL METHODOLOGY

B.1. Qualitative Interviews

Ninety-six interviews were conducted to clarify constructs (e.g., what constitutes "codification creep" in practice), refine empirical measures (e.g., unplanned novelty in the form of weather), and provide illustrations of mechanisms.

All procedures involving human participants were reviewed and approved through an author's home institution's research ethics oversight process for minimal-risk social–behavioral research.[i] Semi-structured interviews followed a protocol organized into eight domains: (1) background; (2) organizational learning and knowledge accumulation; (3) tacit routines vs. codified standards; (4) transferability/applicability of organizational memory; (5) the impact of codified standards on plasticity and performance; (6) (negative) learning effects; (7) balancing standardization and plasticity; and (8) concluding reflections. The guide comprised 23 prompts with probes to elicit examples, mechanisms, and counterfactuals (e.g., Q6–Q8 on tacit vs. codified knowledge; Q12–Q17 on adaptation, standards, and negative learning). The final guide used in the field mirrored the version reproduced in the interview materials.

The eight-domain protocol (Background; Organizational Learning; Tacit vs. Codified; Transferability; Impact of Standards; Negative Learning; Balancing; Closing) mapped to theoretical concepts. Question blocks Q6–Q8 elicited examples of tacit routines and codified standards; Q12–Q14 probed adaptive constraints; Q15–Q17 targeted "negative learning" episodes; Q18–Q20 solicited design choices that balance standardization with flexibility.

[i] This research protocol was approved by the McMaster Research Ethics Board (MREB) on November 17th, 2024 11:42:07 AM as project 7397. The public record is available here: https://macrem.mcmaster.ca/Personalisation/DownloadTemplate/1115.

We employed purposive recruitment supplemented by professional-network referrals. Candidate participants were approached via individualized messages sent to publicly available professional addresses (e.g., LinkedIn, organizational webpages). Interviews were conducted primarily via secure video conferencing; a minority occurred by telephone or in person (e.g., at industry conferences). At the outset, the interviewer introduced the study, confirmed consent (and recording preference), and reiterated withdrawal rights and confidentiality terms. Interviews were conducted between February 2024 and June 2025.

Interviews averaged 58 minutes (median = 56; range = 32–104). Where participants declined recording, interviews proceeded for comparable durations with verified notes. We sought heterogeneity on organizational role (e.g., EPC/utility senior managers, regulators, technical experts, project controls/QA, supply chain partners, and industry advisors/retirees), reactor technologies, geographies, and project life cycle exposure (first of a kind vs. subsequent builds). The final sample comprised 96 participants distributed as follows: senior managers (28), regulators (18), technical experts (22), project controls/QA (12), supply chain/vendor stakeholders (8), and industry consultants or retired executives (8). Appendix Table II summarizes the interview participant categories by sample size, modes of interview, whether it was recorded, mean length of interview, and primary observed themes.

— Insert Appendix Table II Interview Subjects —

We follow a two-stage coding strategy. First, we apply a structured, deductive template derived from the paper's constructs (transferability vs. plasticity of knowledge, codification (explicit knowledge capture), and novelty (planned vs. unplanned)) to facilitate integration with the quantitative analysis. Second, we conduct inductive open coding to surface mechanisms (e.g., document proliferation, change control dynamics, tacit workaround practices, weather driven resequencing) and boundary conditions. The codebook iteratively evolved across four versions with explicit inclusion/exclusion rules and exemplar excerpts. We used NVivo for data management and queries and maintained analytic memos and an audit trail (decisions, code merges/splits, negative cases).

The interviews provided grounding for the theoretical mechanisms proposed in the paper. Across roles, respondents consistently described the slow accumulation of procedures that, over time, crowded out the judgment and flexibility once prized in earlier projects. Consistent with a triangulation strategy, these interview patterns aligned with publicly available online materials and archival documents reviewed for the study (e.g., industry reports, regulatory filings, and construction records), and we found no systematic contradictions; the interviews generally supported both the paper's findings and the external documentary evidence.

B.2. Regulatory Burden Variable

We collect regulatory documents from official national sources for each country in our sample. We identify the highest nuclear regulatory authority or government repository as a source for each country. For example, in Canada we obtain documents from the Canadian Nuclear Safety Commission (CNSC), in France, we gather regulations and technical guides from the Autorité de Sûreté Nucléaire (ASN), in Germany, we rely on the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) portal. We applied this approach across all countries. We prioritize these primary sources because they are authoritative and comprehensive to capture the full set of nuclear regulation in each jurisdiction. These data provide a consistent account of the nuclear regulations in force for each country-year.

B.2.1. Retrieval Across Jurisdictions and Languages

We access each regulator's official website or digital archive to locate nuclear safety laws, codes, and regulatory standards. In many cases, the agencies provide document libraries or databases that we could query by year or topic. We used built-in search tools on these sites, supplemented by translation services and bilingual collaborators to interpret non-English materials. For older documents and those not digitized, we turn to archival sources. We consult national libraries, official gazettes, and the Internet Archive to find historical versions of nuclear regulations.

B.2.2. Constructing Annual Page Counts

After obtaining the documents, we construct the *Regulatory Burden* variable as the number of pages of nuclear regulation in each country-year. We defined "nuclear regulation" to include national laws, legally binding regulations, and officially issued regulatory requirements specific to nuclear power plant safety and construction. This encompasses primary legislation (e.g. nuclear energy acts) and detailed safety regulations or mandatory technical standards, and in some cases formally issued regulatory guides when these carried prescriptive requirements. For each document, we record its length in pages using the document's own pagination (for PDFs and print copies, the last page number was taken as the count). If a document was available only as a scan or text, we convert it to PDF or another consistent format to count pages reliably.

To determine the total pages per year, we aggregated the lengths of all relevant documents in force during that year. We track the introduction, amendment, and repeal of regulations over time to decide which documents contributed to a given year's total. Our procedure was as follows: (1) For the first year a country had any nuclear regulation, we summed the pages of all nuclear regulations enacted up to that year. (2) When new regulations were introduced, we added their page counts to the total from that year onward. (3) We took care to avoid double-counting content. If a new law superseded an older one, we removed the old law's pages once the new law took effect. (4) We leveraged legislative archives and databases to pinpoint when each regulation was active. Some countries had systems allowing us to view historical versions of nuclear regulations, enabling precise year-by-year inclusion.

In practice, it was not always possible to find an exact page count for every single country-year, especially in early decades or for minor regulatory changes; however, by combining official records and historical data, we developed reasonable estimates to fill gaps. In our final dataset, the *Regulatory Burden* measure ranges from roughly 20 to about roughly 4,500 pages of regulation per country-year, with a mean of approximately 652 pages.

B.2.3. Ensuring Consistency Across Countries and Time

A key challenge was ensuring that our regulatory page count could be consistently interpreted across different countries and years. We address this by applying uniform inclusion criteria and validation checks: (1) We consistently include only those pages that pertained to formal nuclear-specific regulation. Counts for each country-year are based on documents serving a similar function (establishing rules for nuclear plant design, construction, operation, safety, etc.). (2) We exclude general regulations not specific to nuclear activities, as well as internal guidelines that were not issued as official requirements. (3) While page layouts differ by source (legal texts vs. regulatory manuals), we assume a printed page is a rough common denominator of content volume. We did not attempt to normalize for font size or word count, but by using official documents, we relied on the standard formats used by regulators. (4) All page counts are based on one-sided pages as numbered in the documents. We applied a consistent approach to counting (including counting annexes if they contained binding rules, but excluding purely explanatory appendices and covers) to ensure fairness across sources. (5) For each country, we maintain the continuity of the measure over time. If a country's regulations remained unchanged for a stretch of years, we kept the page count constant for those years, reflecting that the formal burden was stable. When changes occurred, we update the series accordingly, as described above. (6) We cross-check the trends and levels of our page-count data against qualitative expectations and external information.

B.2.4. Scope and Limitations of the Measure

It is important to note that a "page" of regulation is a coarse metric, not all pages are equally dense or demanding. However, given the broad scope of our study, counting pages was a practical and transparent way to approximate regulatory burden across many contexts. This approach mirrors techniques in regulatory studies where the volume of legislation (number of pages, word count, or byte size of contract) is used as an indicator of complexity or burden (e.g., Dawson & Seater, 2013; Hanisch et al., 2025; Reuer & Devarakonda, 2016). We acknowledge that some pages (e.g. a page listing stringent technical requirements) could impose more burden than others (e.g. a page with a few definitions), but we assumed these differences even out when aggregating dozens or hundreds of pages. The primary goal was to capture the growth of codified rules over time, rather than to estimate the impact of a page.

Additionally, we clarify what our regulatory burden variable does and does not capture. By design, this measure focuses on formal laws and rules written explicitly for the nuclear power industry. Our page counts largely reflect safety requirements, licensing rules, technical standards, and other mandates that nuclear plant builders/operators must adhere to under nuclear-specific legislation. We deliberately exclude broader regulatory layers such as general labor laws, environmental regulations, building codes, or other industry-agnostic rules. Those broader regulations certainly affect nuclear projects and contribute to the overall burden of building a plant, but they apply to many industries and are not part of the nuclear regulatory corpus per se. Including them would vastly increase the complexity of data collection and introduced comparability problems (since general regulations are not targeted to nuclear industry alone).

Our measure, therefore, should be interpreted as the *nuclear-specific* regulatory burden. It likely underestimates the total regulatory burden on a nuclear construction project in absolute terms, because a project must comply with both nuclear-specific rules and all the general laws of the land. However, we argue that nuclear regulations are the most salient component of the burden unique to the nuclear industry, and thus a “first-best” proxy for the overall regulatory stringency faced by nuclear projects. In other words, while a nuclear builder also deals with generic construction regulations, what distinguishes nuclear projects is the additional layer of nuclear-specific rules and it is that layer our metric captures.

In managing the heterogeneity of this variable, we remain aware of its limitations. Different countries might have different styles of regulation (some use very detailed prescriptive rules, others more principle-based shorter regulations). This could mean that page counts are not a perfect one-to-one comparison of regulatory strictness. Any measurement noise or bias would likely be absorbed by our use of country fixed effects in analysis, which control for time-invariant differences across countries. The time-variation within each country (i.e., how much its own regulations expanded) is the key signal needed from the *Regulatory Burden* variable.

B.3. Nuclear Reactor Technologies

The reactor models in this study utilize a range of nuclear reactor technologies as classified by the IAEA. These technologies are differentiated primarily by their distinct choices of coolant (e.g., light water, heavy water, gas) and moderator materials. We employ these classifications to generate the reactor technology fixed effects used in our regression analyses to control for time-invariant heterogeneity across technology types. Appendix Table III provides the definitions for the specific reactor technologies included in our study.

— Insert Appendix Table III Nuclear Reactor Technologies —

B.4. Containment Building Types

The variable *Containment Building Complexity* relies on a ranking of the complexity of containment building materials as scored by two independent engineers. Appendix Table IV describes the eight categories of containment building materials and the ranking value assigned to that category for this variable, where 1 is least complex and 8 is most complex. A higher value indicates a greater degree of engineering intricacies and construction challenges associated with that type of material for the containment building. For example, pre-stressed concrete structures involve additional processes such as tensioning steel tendons within the concrete to enhance strength, which adds to construction time and complexity.

— Insert Appendix Table IV Containment Building Types —

C. ECONOMIC AND ENVIRONMENTAL IMPACT

C.1. Economic: Excess Costs

Nuclear reactors, like other megaprojects, are prone to significant excess costs, especially when construction timelines are extended. For example, Boston's Big Dig was initially estimated at $2.5 billion but ultimately cost over $22 billion. Similarly, the Hong Kong-Zhuhai-Macau Bridge exceeded its budget by HK$10 billion, and the Vogtle nuclear power plant—the most expensive project in U.S. history—has surpassed its original $14 billion estimate, now projected to cost $31–36.8 billion, an overrun of 121–163% (Hiller, 2024).

This section estimates the impact of reactor model experience on excess costs for a hypothetical nuclear reactor project started in 2020. Using data from the International Energy Agency (IEA) (IEA, 2020), we estimate the minimum, mean, median, and maximum excess costs for this hypothetical reactor project as a function of reactor model experience. The

International Energy Agency's cost estimates assume a seven-year construction timeline and vary by reactor size and geographic region, with the lowest costs observed in Russia, South Korea, and China and the highest in Europe and the U.S.

From these assumptions, we calculate an expected daily cost for each reactor in our dataset. Excess costs are derived by multiplying this daily cost by the number of days exceeding the expected seven-year construction timeline. Although this approach has limitations, it provides a reasonable approximation. An anecdotal example of excess costs being closely related to construction duration is the Vogtle nuclear power plant. Vogtle's construction duration more than doubled from the planned seven years to 15 years, illustrating how delays drive cost escalation. The construction of the Vogtle nuclear power plant lasted 114% longer than originally estimated and was 121–163% over budget.

The results, presented in Appendix Table V, show that *Reactor Model Experience* has a significant positive impact on excess costs across all four measures of costs, with higher levels of *Reactor Model Experience* correlating with greater excess costs. Each additional reactor worth of experience represents a mean excess cost of \$39,867,475.50 ($p \approx 0.00$). However, that can depend significantly on reactor technology and location, with an average minimum excess cost of \$23,847,515.47 ($p \approx 0.00$) and an average maximum excess cost of \$76,506,630.31 ($p \approx 0.00$) for each additional reactor worth of experience.

In addition to *Reactor Model Experience*, other variables such as *Regulatory Burden*, *Reactor Power Output*, and *Containment Building Complexity* also significantly influence excess costs. *Regulatory Burden* is positively correlated with excess costs, which suggests that increased regulatory scrutiny and compliance costs contribute to financial inefficiencies. Larger reactors, those with higher electrical outputs, also tend to have higher excess costs, as reflected in the positive coefficients for *Reactor Power Output*. Interestingly, *Containment Building Complexity* has a negative effect on excess costs, indicating that more complex containment structures are associated with fewer or smaller overruns.

— Insert Appendix Table V Excess Costs —

C.2. Environmental: Excess Carbon Emissions

Nuclear reactors are among the cleanest sources of energy available with current technology. When measured in lifecycle carbon emissions—which include not only the emissions from fuel burning but also those from mining, transportation, and maintenance over a power plant's lifetime—nuclear energy produces just 6 tonnes of CO_2 per GWh of electricity. In comparison, coal produces 970 tonnes, oil 720 tonnes, natural gas 440 tonnes, hydro 24 tonnes, wind 11 tonnes, and solar 53 tonnes of CO_2 per GWh (Ritchie and Roser, 2024). Consequently, extended construction timelines for planned reactors result in significant, unplanned carbon emissions.

According to the IEA, the global average CO_2 emissions per GWh in 2019 were 475 tonnes (Global Energy & CO_2 Status Report 2019—Analysis, 2019). For each GWh of electricity, a delay in nuclear power plant deployment contributes an excess of 469 tonnes of CO_2—emissions that could have been avoided by completing the reactor on time.

In this section, we estimate the excess carbon emissions resulting from construction delays beyond the planned seven-year construction timeline for a nuclear reactor, as described in the previous section on excess costs. Our calculation derives the excess emissions by estimating the CO_2 savings that could have been achieved globally if the reactors were completed within the planned timeframe. Reactors completed earlier displace energy from higher-emission sources, reducing global CO_2 emissions. Conversely, delays force reliance on the current energy mix, which includes more carbon-intensive sources.

It is important to note that our estimates of excess carbon emissions are conservative. Nuclear power plants are more likely to replace carbon-intensive energy sources, such as coal, rather than the average energy mix, which includes cleaner sources like wind, solar, hydro, and other nuclear power plants. Coal-fired power plants, which are the most likely to be displaced by nuclear energy, emit between 740 and 910 tonnes of CO_2 per GWh. By using a conservative figure of 469 tonnes of excess CO_2 per GWh, we likely underestimate the true environmental cost of construction delays.

The results of this analysis are presented in Appendix Table VI. Model 1 serves as the control model. In Model 2, we introduce the *Reactor Model Experience* main effect. For the longer construction resulting from each deployment of a reactor model, 287.27 thousand tonnes ($p \approx 0.00$) of excess CO_2 are emitted. In Model 3, we introduce the interaction *Reactor Model Experience* × *Unexpected Heavy Rain* ($\beta_3 = 2.76$, $p \approx 0.00$), which is statistically significant. In Model 4, we additionally introduce the interaction *Reactor Model Experience* × *Novel Containment Building* ($\beta_5 = -721.38$, $p = 0.08$). For a first-of-a-kind reactor, one unexpectedly heavy day of rain would have caused delays equivalent to 2,760 excess tonnes of CO_2. For the 33rd reactor (e.g., Vogtle-1), a single unexpected day of heavy rain would have caused 91,080 tonnes of excess CO_2. Two days of unexpectedly heavy rain for the same reactor would have caused 182,160 tonnes of excess CO_2, and so on.

— Insert Appendix Table VI Excess Carbon Emissions —

D. SUPPLEMENTAL ANALYSES

D.1. Construct Validity

In this supplementary analysis, we test the robustness of our main findings to an alternative measure of codified knowledge and planned novelty. While the nuclear reactor is the most complex, and certainly most critical, component of a nuclear power plant, the reactor containment building, while less technically complex, is the largest civil works component of the power plant. In this specification, we measure experience with a containment build type rather than with a nuclear reactor model. Additionally, we measure planned novelty as the introduction of a novel reactor model to a standard containment building type. In effect, this specification flips the experience and planned novelty measures from our main model.

The results of this analysis are presented in Appendix Table VII. Model 1 serves as the control model. In Model 2, we introduce the *Containment Building Experience* main effect, which is statistically significant and in the predicted direction ($\beta_1 = 10.61$, $p = 0.03$). Model 3 includes the interaction *Containment Building Experience* × *Unexpected Heavy Rain*, which remains significant and in the predicted direction ($\beta_3 = 0.18$, $p \approx 0.00$). Model 4 also incorporates the planned novelty interaction *Containment Building Experience* × *Novel Reactor Model*. Our main findings are consistent in this new operationalization ($\beta_5 = -13.79$, $p = 0.09$), albeit with lower statistical significance here.

— Insert Appendix Table VII Containment Building Experience and Novel Reactor Model —

D.2. Technical Context

D.2.1. Reactor Size

We control for reactor size in our main model. In this section we assess the sensitivity of our results to reactor size by running unique regressions for a variety of reactor sizes. We divide reactors into four categories based on their electrical output: reactors with a capacity of at least 20 MWe, at least 300 MWe, at least 800 MWe, and at least 1000 MWe. The categories are based on common size categories of nuclear reactors within the PRIS database. Our results are similar across reactor size specifications.

The results of this analysis, presented in Appendix Table VIII, reveal that *Reactor Model Experience* continues to have an effect on construction duration across reactors of varying sizes, although the magnitude of this effect varies. For reactors with capacities of at least 300 MWe (Model 1: $\beta 1 = 35.97$, $p \approx 0.00$) and those with capacities with at least 800 MWe (Model 2: $\beta_1 = 31.09$, $p = 0.01$), *Reactor Model Experience* increased construction duration. The effect of *Reactor Model Experience* on very large reactors (Model 4) is not statistically significant ($\beta_1 = 18.67$, $p = 0.34$); we posit that larger reactors may involve complexities that diminish the impact of prior experience. It is important to note that our sample size of very large reactors (Model 4) is relatively small (n = 176). We also find that factors such as *Reactor Power Output* and *Containment Building Complexity* have a greater impact on construction time for larger reactors. Overall, these findings suggest that while reactor model experience remains a key driver of construction duration, the effect is somewhat attenuated for larger reactors, which may involve additional technical challenges that are not fully impacted by prior experience.

— Insert Appendix Table VIII Reactor Size Subsamples —

D.2.2. Overspecification with Technical Variables

In this supplementary analysis, we test the robustness of our main findings by incorporating several technical variables related to reactor design and structural characteristics (including reactor vessel dimensions and shape), fuel properties and refueling strategies (such as fuel material, form, assembly geometry, cladding material and thickness, refueling frequency, and refuel type), core characteristics (including active core dimensions and power densities), coolant and steam systems (including coolant type, number of pumps, steam generators, and turbine type and speed), containment features (such as containment type and shape), operational factors (such as operator name), and key material choices (including moderator and fuel cladding materials). The interested reader can find a brief description of the technical variables in Appendix Table IX.

The results of this analysis are presented in Appendix Table X, which follows the description of the technical variables. Model 1 serves as the control model. In Model 2, we introduce the *Reactor Model Experience* main effect, which remains in the predicted direction ($\beta_1 = 31.18$, $p \approx 0.00$). Model 3 includes the interaction *Reactor Model Experience* × *Unexpected Heavy Rain*, which remains in the predicted direction ($\beta_3 = 0.20$, $p = 0.01$). Model 4 incorporates the interaction *Reactor Model Experience* × *Novel Containment Building*. While this coefficient reduces construction duration as expected, it is must less statistically significant ($\beta_5 = -26.25$, $p = 0.51$). We believe this is because the inclusion of a large set of new technical variables (36 in total) accounts for the planned novelty previously captured by the *Novel Containment Building* variable. Overall, our results remain largely robust despite the overspecification of technical variables.

— Insert Appendix Table IX Technical Control Variables —

— Insert Appendix Table X Overspecification with Technical Variables —

D.3. Regulatory and Geopolitical Environment

D.3.1. Experience and Regulatory Burden

This analysis examines the interaction *Reactor Model Experience* × *Regulatory Burden*. If regulation significantly contributes to explaining our main effect, it is plausible that regulatory burden interacts with codified knowledge in a manner that disproportionately intensifies with increasing reactor model experience. This interaction could potentially overshadow the main effect. An ideal test would compare two conditions: one with low or no regulatory burden and another with high regulatory requirements, while varying reactor model experience. Lacking the ideal experimental setup, we instead interact *Reactor Model Experience* with *Regulatory Burden*.

The results of this analysis are presented in Appendix Table XI. Model 1 serves as the control model. In Model 2, we introduce the *Reactor Model Experience* main effect, which remains in the predicted direction ($\beta_1 = 14.36$, $p = 0.08$). Model 3 incorporates the *Regulator Burden* variable, which is, as expected, meaningful ($\beta_2 = 1.61$, $p \approx 0.00$). An extra page of regulation increases construction duration by 1.6 days. Model 4 introduces the interaction between *Reactor Model Experience* × *Regulatory Burden*. This relationship is neither meaningful nor statistically significant ($\beta_3 = -00.00$, $p = 0.61$). Overall, we find no evidence that our main results are affected by an increasing *Regulator Burden*.

— Insert Appendix Table XI Regulatory Burden Interaction —

D.3.2. Sensitivity to the Chernobyl Nuclear Disaster

We explore the sensitivity of our results to the Chernobyl nuclear disaster, a pivotal event in the history of nuclear energy. The Chernobyl disaster, which occurred in Ukraine in 1986 when it was part of the Soviet Union, had profound and lasting effects on nuclear regulation and safety standards all around the world. We consider whether the disaster influenced construction durations differently in its aftermath, potentially confounding our main findings. We test whether nuclear power plants whose construction began in the ten-year period following Chernobyl experienced significant changes in reactor construction durations compared to power plants that started construction in the period ten years before the disaster, either due to heightened regulatory scrutiny or shifts in industry practices.

We introduce a post-Chernobyl variable. Additionally, we explore whether the interaction between the post-Chernobyl period and *Reactor Model Experience* has any notable impact on construction times. Given that the post-Chernobyl era is associated with more stringent regulatory environments and changes in public perception of nuclear energy, we hypothesize that these factors could alter the baseline relationship between *Reactor Model Experience* and *Construction Duration*.

The results of this analysis are presented in Appendix Table XII, which includes the interaction between post-Chernobyl status and reactor model experience. We find that the post-Chernobyl period is associated with a significant increase in *Construction Duration*, particularly in the earlier years following the disaster. Our main effects suggest that nuclear power plants that began construction in the post-Chernobyl period required, on average, an additional 1,044 (p = 0.02) days to complete construction compared to those whose construction began in the pre-Chernobyl period. Our interaction effects indicate that the longer construction times were more pronounced for projects that started closer to the disaster, and that this effect decreased over time. According to our estimates, the effects of the Chernobyl disaster on construction times would be negligible 40 years after the disaster ($p \approx 0.00$), in the year 2026. It is important to clarify that the purpose of this study was not to investigate the effects of the Chernobyl disaster on nuclear power plant construction times. We include the post-Chernobyl period variable as a control and mention these results for illustrative purposes only.

Importantly, the interaction between the post-Chernobyl period and *Reactor Model Experience* is not statistically significant ($\beta_4 = 26.15$, $p = 0.60$), suggesting that the effect of *Reactor Model Experience* on *Construction Duration* remains stable, even in the aftermath of the disaster when nuclear power plant construction slowed considerably.

Overall, these results indicate that while the Chernobyl disaster had a notable impact on construction timelines, our main findings regarding *Reactor Model Experience* and *Construction Duration* hold. This analysis provides further confidence in our results, given it holds in the context of arguably the most significant disaster in the history of nuclear energy.

— Insert Appendix Table XII Chernobyl Nuclear Disaster —

D.3.3. Geopolitical Events and Cultural Distance

This analysis investigates the impact of geopolitical events and cultural distance on the relationship between *Reactor Model Experience* and *Construction Duration*. The nuclear energy industry can be influenced by global political dynamics, regulatory environments, and cross-cultural factors. Geopolitical events, such as wars, oil embargoes, and international crises, can disrupt the construction of nuclear plants by introducing uncertainty, shifting political priorities, or altering economic conditions. Additionally, cultural differences, captured by Hofstede's cultural distance metric (Hofstede, 1980; Kogut and Singh, 1988), may affect organizational practices, regulatory compliance, and project management, which in turn could influence construction timelines.

To assess these effects, we introduce several variables into our model, including geographic distance, Hofstede cultural distance, and several major geopolitical events, such as the Suez Crisis, the OPEC embargo, the Iranian Revolution, the Iran-Iraq War, and the Gulf War of 1990. *Hofstede Distance* measures the cultural distance between the country where the plant project is located and home country of the general contractor; this variable takes a value of zero when the project takes place in the general contractor's home country. We follow the formula from Kogut and Singh (1988) based on the four dimensions proposed by Hofstede (1980). We also consider the effect of a firm's home country membership in the IAEA.

The results of this analysis are presented in Appendix Table XIII. Our findings suggest that geopolitical events, such as the Iranian Revolution ($\beta_{11} = -476.55$, $p = 0.01$) and the Iran-Iraq War ($\beta_{12} = -499.07$, $p \approx 0.00$), have a significant negative impact on *Construction Duration*, indicating that these events may have resulted in overall faster construction times, possibly by increasing energy prices. However, other geopolitical events, such as the OPEC embargo (β_{10} = –24.84, p = 0.87) and the Gulf War of 1990 (β_{13} = 100.06, p = 0.74), do not show significant effects. Additionally, while geographic (β_6 = –0.02, p = 0.57) and Hofstede cultural (β_7 = –28.86, p = 0.69) distances are included in the model, they do not appear to significantly alter construction timelines, suggesting that other factors may be more influential in this context. A firm's home country IAEA membership substantially reduces construction duration (β_8 = –1,134.02, $p \approx 0.00$).

Overall, these results imply that while geopolitical events can influence construction duration, our main findings regarding reactor model experience and construction duration remain robust even when accounting for these additional variables.

— Insert Appendix Table XIII Geopolitical Events and Cultural Distance —

D.3.4. Country Exclusions (China, Russia, and Iran)

This analysis tests the sensitivity of our main findings to the exclusion of China, Russia, and Iran from our dataset. These countries possess unique characteristics in their nuclear power programs that could influence construction durations differently compared to nuclear reactors built in other nations. China's rapid expansion of nuclear energy capacity is largely driven by state-led initiatives and substantial government investments, which may accelerate construction times independently of organizational experience. Russia's nuclear industry is also predominantly state-controlled and often engages in international projects with distinct contractual and regulatory frameworks. Iran's nuclear program was interrupted by the Islamic revolution of 1979 and faces both international sanctions and geopolitical challenges that can cause atypical construction delays unrelated to technical or organizational factors. We exclude these countries in this analysis to test whether our results are disproportionately affected by these exceptional national contexts and to assess the generalizability of our findings across a more homogeneous set of countries.

Appendix Table XIV presents the results of this analysis. Model 1 serves as the control model. Model 2 introduces the *Reactor Model Experience* main effect, which remains in the predicted direction ($\beta_1 = 13.25$, $p = 0.07$). Model 3 introduces the interaction *Reactor Model Experience* × *Unexpected Heavy Rain*, which remains consistent with our main findings ($\beta_5 = 0.20$, $p = 0.01$). Model 4 incorporates the interaction *Reactor Model Experience* × *Novel Containment Building* ($\beta_3 = -89.75$, $p \approx 0.00$). These results suggest our main results are robust to the exclusion of China, Russia, and Iran.

— Insert Appendix Table XIV Country Exclusions: China, Russia, and Iran —

E. APPENDIX REFERENCES

Dawson, J. W., & Seater, J. J. (2013). Federal regulation and aggregate economic growth. *Journal of Economic Growth*, 18(2), 137–177.

Hiller, J. (2024). A massive U.S. nuclear plant is finally complete. It might be the last of its kind. *Wall Street Journal*.

Hanisch, M., Graf-Vlachy, L., Häussler, C., König, A., & Cho, T. S. (2025). Kindred spirits: Cognitive frame similarity and good faith provisions in strategic alliance contracts. *Strategic Management Journal, 46*(2), 436–469.

Hofstede, G. (1980). *Culture's Consequences: International Differences in Work-Related Values*. Sage Publications, Beverly Hills, CA.

International Energy Agency. (2019). *Global Energy & CO_2 Status Report 2019*. https://www.iea.org/reports/global-energy-co2-status-report-2019

International Energy Agency. (2020). *Projected costs of generating electricity 2020*. https://www.iea.org/reports/projected-costs-of-generating-electricity-2020

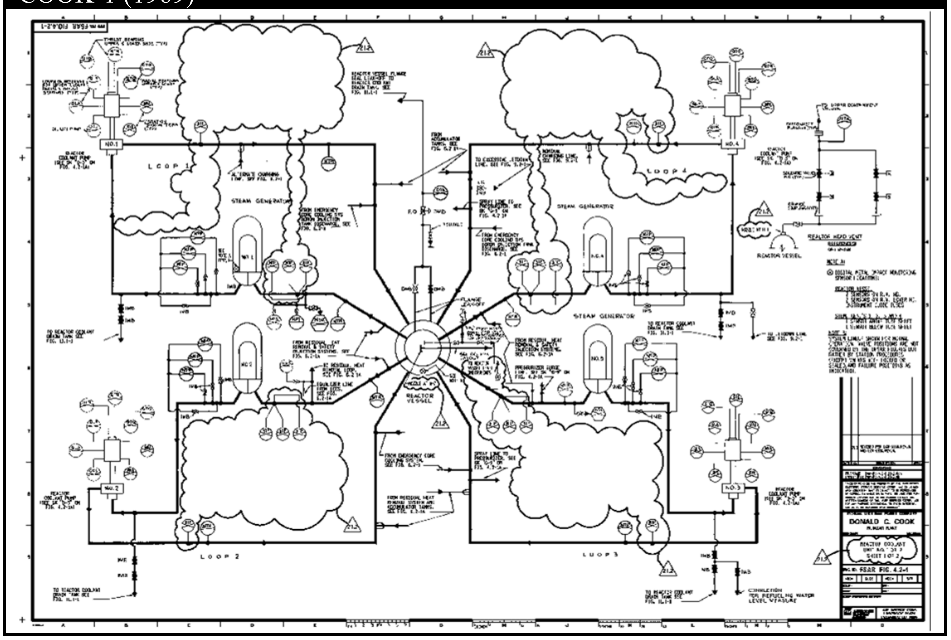
Kogut, B., & Singh, H. (1988). The effect of national culture on the choice of entry mode. *Journal of International Business Studies*, 19(3), 411–432.

Ritchie, H., & Roser, M. (2020). CO_2 emissions. *Our World in Data.*

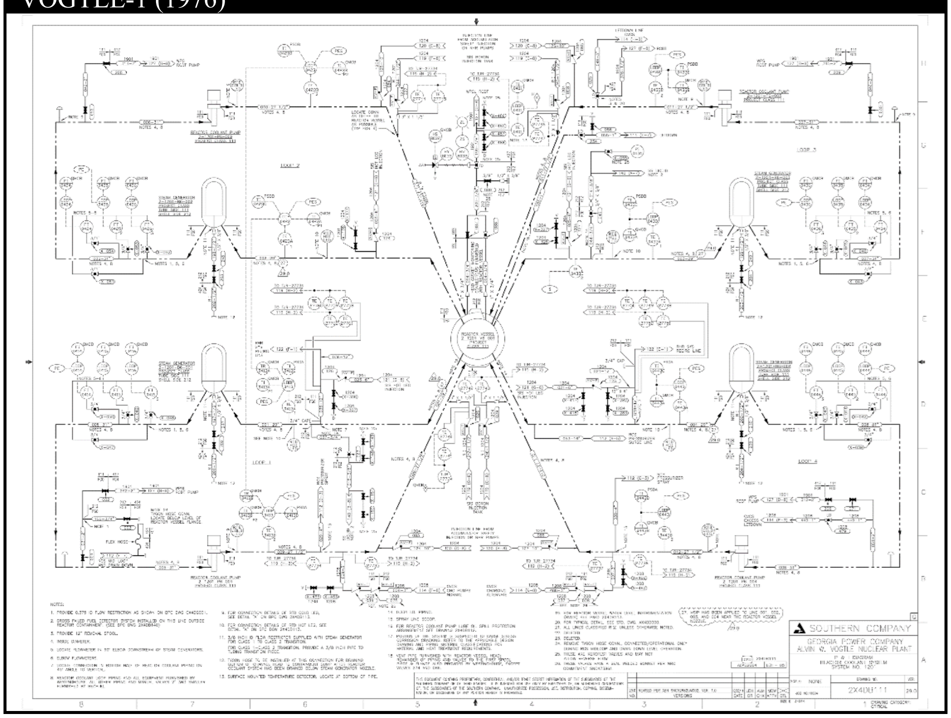
Reuer, J. J., & Devarakonda, S. V. (2016). Mechanisms of hybrid governance: Administrative committees in non-equity alliances. *Academy of Management Journal, 59*(2), 510–533.

APPENDIX FIGURE I REACTOR VESSEL Original plans of the reactor vessels for COOK-1 (top) VOGTLE-1 (bottom). Note the significantly higher density of labels for valves and gauges (represented by small circles) in the VOGTLE-1 diagram compared to COOK-1. Furthermore, VOGTLE-1 plans reflect extensive (even excessive) annotations; for example, Note 8 specifies the specific vendors responsible for standard coolant loop piping and valves, information omitted from the COOK-1 plans.

COOK-1 (1969)

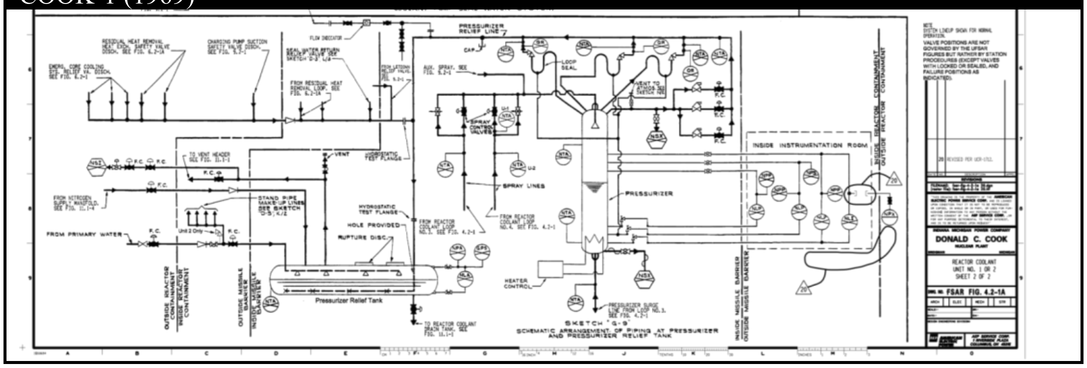


VOGTLE-1 (1976)

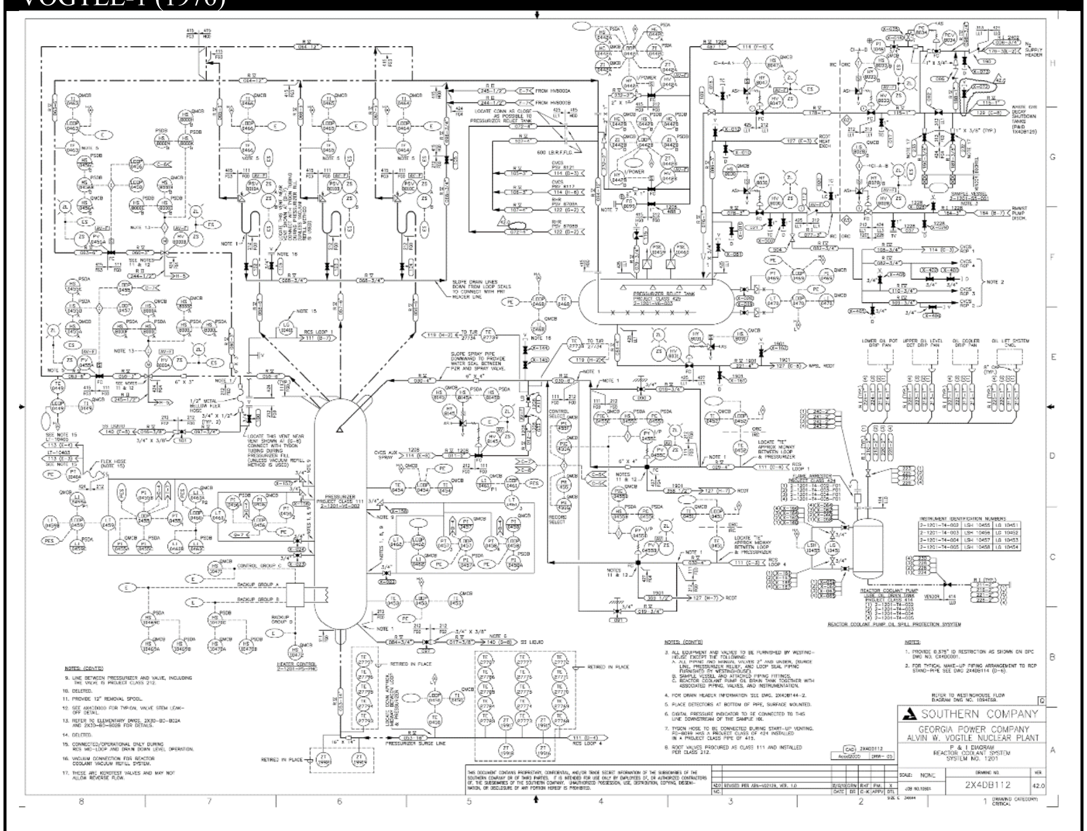


APPENDIX FIGURE II COOLANT SYSTEM Original plans of the coolant systems, including the pressurizer and pressurizer relief tank, for COOK-1 (top) and VOGTLE-1 (bottom). The VOGTLE-1 diagram demonstrates a marked increase in annotations detailing obvious procedures; for instance, Note 3 explicitly documents supplier responsibilities for equipment and valves.

COOK-1 (1969)

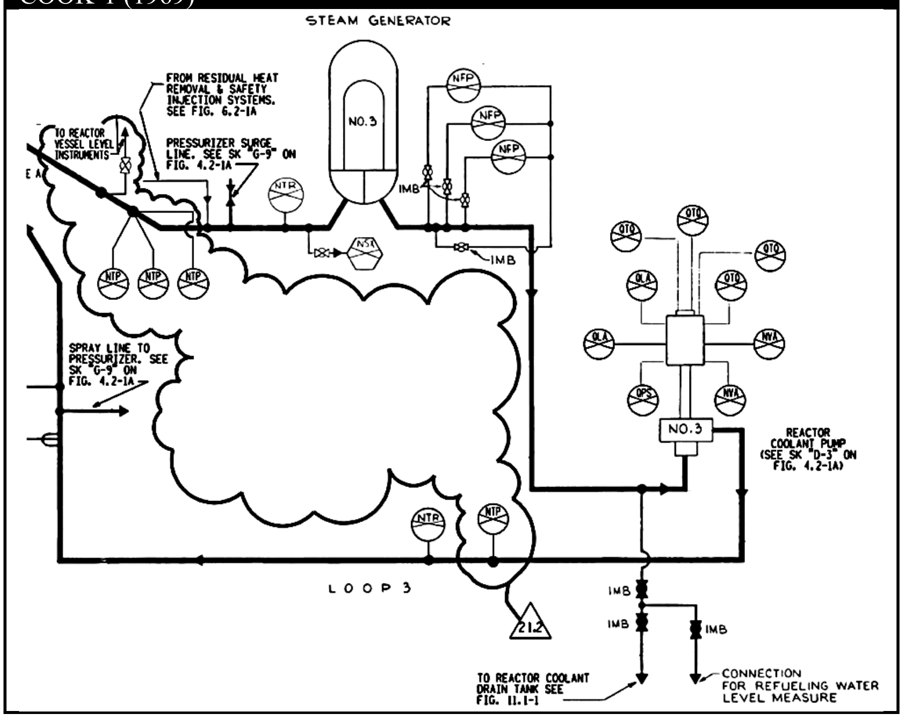


VOGTLE-1 (1976)

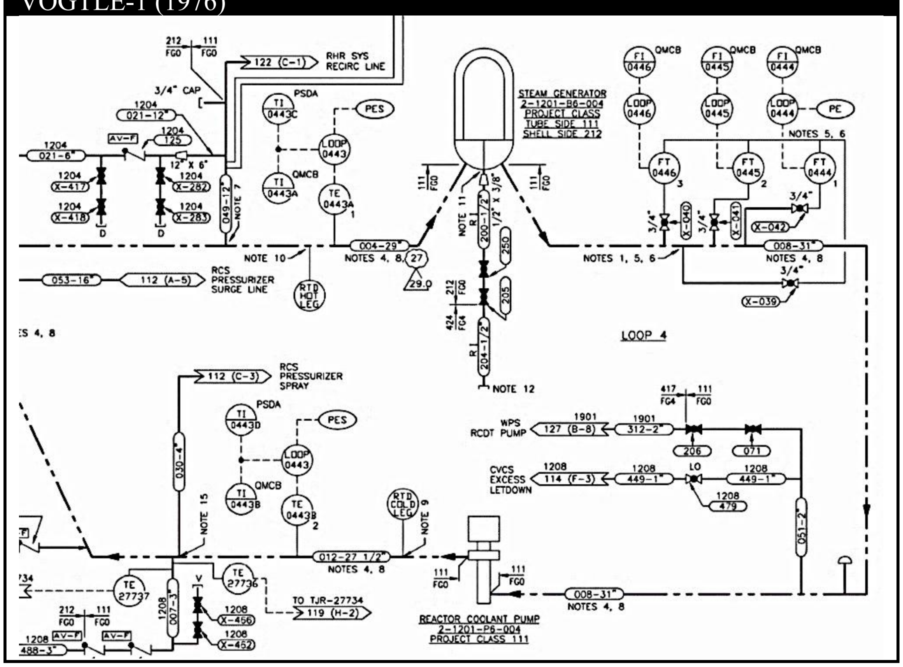


APPENDIX FIGURE III STEAM GENERATOR Zoomed-in view of the steam generator plans for COOK-1 (top) and VOGTLE-1 (bottom). Compare the number of explicit references to detailed notes. The VOGTLE-1 diagram includes numerous callouts notes linking components to specific instructions and annotations, while the COOK-1 diagram contains few such references.

COOK-1 (1969)

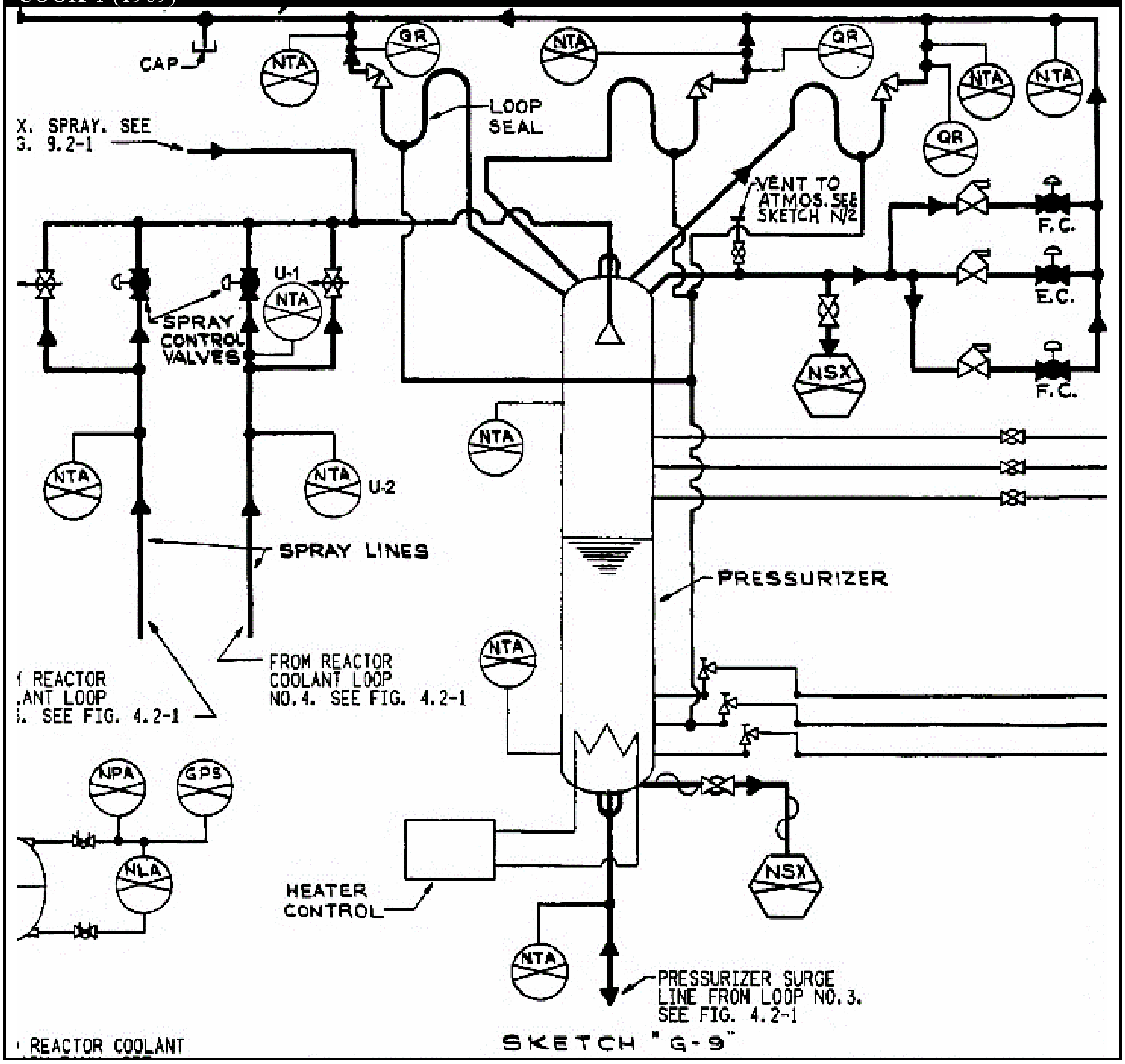


VOGTLE-1 (1976)



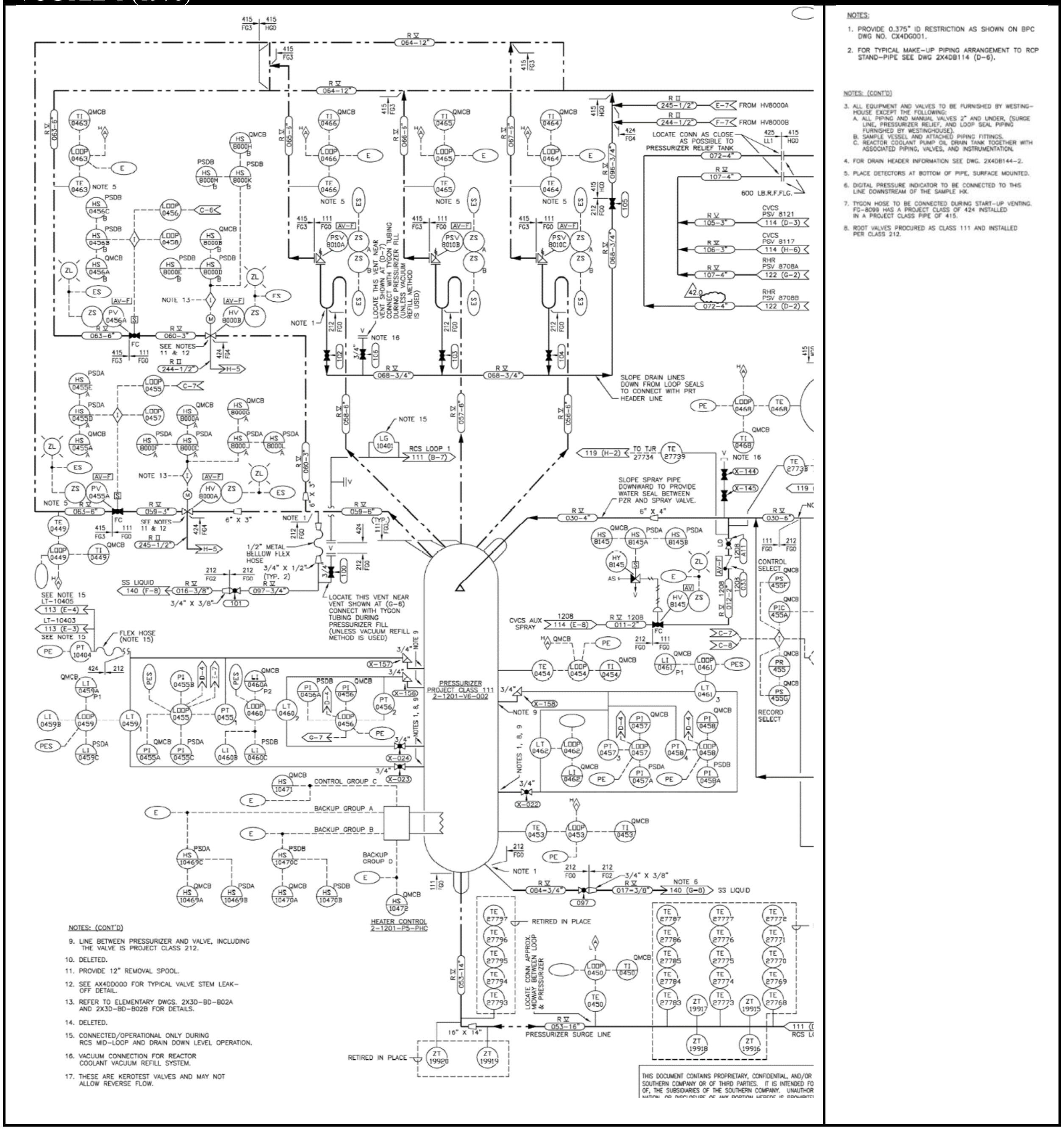
APPENDIX FIGURE IV PRESSURIZER: COOK-1 Zoomed-in view of the pressurizer plans for COOK-1. Note the relative sparsity of the diagram, characterized by a lack of detailed annotations, specific component labeling, and references to external notes.

COOK-1 (1969)



APPENDIX FIGURE V PRESSURIZER: VOGTLE-1 Zoomed-in view of the Pressurizer plans for VOGTLE-1. Observe the high density of information, including extensive annotations, specific labeling of all minor components with unique identification numbers, and frequent references to detailed notes.

VOGTLE-1 (1976)



APPENDIX TABLE I COOK-1 VS. VOGTLE-1 COMPARISON

Reactor *Plant*	**COOK-1** *Donald C. Cook Nuclear Plant*	**VOGTLE-1** *Alvin W. Vogtle Electric Generating Plant (Plant Vogtle)*
Reactor Model Experience	8	33
Construction Duration	2125 days	3872 days
Construction Start date	25 March 1969	01 August 1976
Location Country	United States of America	United States of America
Reactor Supplier	Westinghouse Electrical Corp.	Westinghouse Electrical Corp.
Reactor Model	Westinghouse 4 Loop	Westinghouse 4 Loop
Reactor Type	Pressurized Water Reactor (PWR)	Pressurized Water Reactor (PWR)
Location Heavy Unexpected Rain	390 days	401 days
Location Mean Temp.	9.29 degrees Celsius	17.42 degrees Celsius
Location Climate	Mild Temperature	Subtropical
Location Water Access	Inland near a lake	Inland near a river
Reactor Reference Nr.	US – 315	US – 424
Refueling Frequency	18 months	18 months
Refueling Percentage	33%	33%
Refuel Type	OFF-line	OFF-line
Active Core Diameter	3.4 m	3.4 m
Original Design Net Power	1,030 MWe	1122 MWe
Latest Gross Power	1,131 MWe	1,229 MWe
Inside Reactor Shell Diameter	4.4 m	4.4 m
Nr. Fissile Fuel Assemblies	193	193
Nr. of Steam Generators	4	4
Steam Generator Type	Vertical	Vertical
Pumps / Coolant Loop	1	1
Geological Complexity	Low	Low
Seismic Hazard Level	Low	Low

APPENDIX TABLE II INTERVIEW SUBJECTS *Category* denotes the employment field or role of the interview subjects: senior executives lead a general contractor or utility, and project managers assigned to work on specific projects in roles like quality assurance or project control. *Subjects* indicates the number of distinct individuals interviewed with one interview per subject. *Recorded* is the number of interviews that were recorded; written notes were taken in the remainder. *In-Person* is the number of in-person interviews; the remainder were conducted over videoconferencing or telephone. *Duration* is the mean interview duration with the range listed in brackets ([Min–Max]). *Key Themes* were summarized from semi-structured interviews organized by the guide's domains (organizational learning; tacit vs. codified knowledge; transferability/plasticity; negative learning; balancing standardization and flexibility). Procedures for consent, optional recording, and note taking followed the approved protocol.

Category	Subjects	Recorded	In-Person	Duration	Key Themes
Senior Executive	28	12	12	59 [43–76]	Governance; change-control cadence; document proliferation; agility; learning; weather resequencing; decision latency
Regulator	18	6	2	57 [44–72]	Licensing scope & graded approach; hold-point logic; traceability expectations; digital submissions; harmonization
Technical Expert	22	7	12	59 [41–74]	Constructability; weld/NDE planning; model-to-field mismatch; temporary works; commissioning interface; lessons-learned capture
Project Manager	12	4	7	56 [44–68]	Baseline realism & float erosion; KPI proliferation; risk & contingency; batch releases; milestone discipline
Vendor or Supply Chain	8	6	3	56 [43–66]	Long-lead items; equivalency packages; serialization & pedigree; portal usability; inspection scheduling
Consultant	8	6	2	61 [49–74]	Path dependence; codification creep; pruning/simplification levers; contractual incentives for adaptability

APPENDIX TABLE III NUCLEAR REACTOR TECHNOLOGIES

Name	Initials	Description
Boiling Water	BWR	Core boils waters to drive a steam turbine.
Fast Breeder	FBR	Uses fast neutrons for fission. Generates more fissile material than it consumes.
Gas-Cooled	GCR	Uses carbon dioxide or helium coolant with graphite moderator.
High-Temperature Gas-Cooled	HTGR	Uses helium gas coolant and graphite moderator, operating at high temperatures.
Gas-Water Gas-Cooled	GWGCR	Hybrid use of both gas and water cooling, with graphite moderator.
Heavy Water Light Water	HWLWR	Uses a combination of heavy water (deuterium oxide) and light water for cooling and moderation.
Light Water Graphite	LWGR	Uses light water as coolant with graphite moderator.
Pressurized Heavy Water	PHWR	Uses heavy water as a moderator and coolant under high pressure.
Pressurized Water	PWR	Uses pressurized water as both coolant and moderator. Most common nuclear reactor type.
Steam Generating Heavy Water	SGHWR	Heavy water for both cooling and moderation. Generates steam directly for turbines.

APPENDIX TABLE IV CONTAINMENT BUILDING TYPES

Containment Building	Description	Complexity
Concrete	Utilizes plain concrete without pre-stressing or significant reinforcement, relying on mass to provide structural integrity.	1
Pre-Stressed Concrete	Involves tensioning steel tendons within the concrete before applying external loads, enhancing the structure’s ability to withstand internal pressures.	4
Pre-Stressed Concrete + Steel	Combines pre-stressed concrete with steel liners or components to improve leak-tightness and structural performance.	7
Pre-Stressed + Reinforced Concrete	Integrates both pre-stressing and reinforcement techniques, offering additional strength and flexibility.	8
Reinforced Concrete	Incorporates steel reinforcement bars within the concrete to resist tensile stresses and improve durability.	3
Reinforced Concrete + Steel	Augments reinforced concrete structures with steel liners or cladding for enhanced containment.	6
Steel	Employs steel plates or shells as the primary structural material, requiring specialized fabrication and welding techniques.	2
Steel + Concrete	Combines steel structures with concrete infill or cladding, leveraging the advantages of both materials.	5

APPENDIX TABLE V EXCESS COSTS The dependent variable *Excess Cost* is measured in units of 1 million USD. Ordinary least squares (OLS) estimation. Robust standard errors are clustered at the firm level. *p*-values are shown in parentheses.

Excess Cost	(Appendix Table V.1) Min Overrun	(Appendix Table V.2) Mean Overrun	(Appendix Table V.3) Median Overrun	(Appendix Table V.4) Max Overrun
Reactor Model Experience	23.85	39.87	37.26	76.51
	(0.00)	(0.00)	(0.00)	(0.00)
Unexpectedly Heavy Rain	0.33	0.55	0.52	1.06
	(0.55)	(0.55)	(0.55)	(0.55)
Novel Containment Building	21.27	35.56	33.24	68.25
	(0.89)	(0.89)	(0.89)	(0.89)
Regulatory Burden	1.13	1.89	1.76	3.62
	(0.00)	(0.00)	(0.00)	(0.00)
Reactor Power Output	0.98	1.63	1.53	3.14
	(0.00)	(0.00)	(0.00)	(0.00)
Reactor Power Density	–0.15	–0.25	–0.24	–0.48
	(0.90)	(0.90)	(0.90)	(0.90)
Containment Building Complexity	–41.00	–68.54	–64.06	–131.54
	(0.19)	(0.19)	(0.19)	(0.19)
Temperature	–34.90	–58.35	–54.53	–111.98
	(0.15)	(0.15)	(0.15)	(0.15)
Temperature Variability	–57.25	–95.70	–89.44	–183.66
	(0.16)	(0.16)	(0.16)	(0.16)
Precipitation	–35.21	–58.86	–55.01	–112.95
	(0.51)	(0.51)	(0.51)	(0.51)
Wind Speed	–26.33	–44.01	–41.13	–84.46
	(0.02)	(0.02)	(0.02)	(0.02)
Daylight	–0.19	–0.32	–0.29	–0.61
	(0.60)	(0.60)	(0.60)	(0.60)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Reactor Manufacturer FE	Yes	Yes	Yes	Yes
Reactor Technology FE	Yes	Yes	Yes	Yes
Observations	599	599	599	599
AIC	9,899.5	10,515.1	10,434.0	11,296.0
R^2	0.404	0.404	0.404	0.404

APPENDIX TABLE VI EXCESS CARBON EMISSIONS The dependent variable *Excess Carbon Emission* is measured in units of 1,000 tonnes of CO_2. Ordinary least squares (OLS) estimation. Robust standard errors are clustered at the firm level. *p*-values are shown in parentheses.

Excess Carbon Emissions	(Appendix Table VI.1)	(Appendix Table VI.2)	(Appendix Table VI.3)	(Appendix Table VI.4)
Reactor Model Experience		287.27	–837.54	–835.67
		(0.00)	(0.02)	(0.02)
Unexpectedly Heavy Rain			–12.64	–12.82
			(0.11)	(0.11)
Reactor Model Experience × Unexpectedly Heavy Rain			2.76	2.80
			(0.00)	(0.00)
Novel Containment Building				2,119.89
				(0.32)
Reactor Model Experience × Novel Containment Building				–721.38
				(0.08)
Regulatory Burden	12.93	13.39	13.96	13.53
	(0.00)	(0.00)	(0.00)	(0.00)
Reactor Power Density	–0.50	–1.20	–3.59	–4.49
	(0.97)	(0.92)	(0.77)	(0.72)
Containment Building Complexity	–2.92	92.84	110.07	88.10
	(0.99)	(0.78)	(0.74)	(0.79)
Temperature	–183.67	–315.57	–291.33	–312.61
	(0.49)	(0.24)	(0.28)	(0.24)
Temperature Variability	–126.16	–385.75	–316.34	–349.02
	(0.77)	(0.38)	(0.47)	(0.43)
Precipitation	–819.88	–776.57	–868.67	–811.65
	(0.16)	(0.18)	(0.14)	(0.16)
Wind Speed	–140.07	–178.55	–162.98	–171.02
	(0.24)	(0.13)	(0.17)	(0.15)
Daylight	–6.65	–6.89	–6.55	–6.72
	(0.08)	(0.07)	(0.08)	(0.08)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Reactor Manufacturer FE	Yes	Yes	Yes	Yes
Reactor Technology FE	Yes	Yes	Yes	Yes
Observations	598	598	598	598
AIC	12,763.0	12,752.3	12,743.8	12,744.1
R^2	0.430	0.442	0.453	0.457

APPENDIX TABLE VII CONTAINMENT BUILDING EXPERIENCE AND NOVEL REACTOR MODEL Ordinary least squares (OLS) estimation. Robust standard errors are clustered at the firm level. *p*-values are shown in parentheses.

Construction Duration	(Appendix Table VII.1)	(Appendix Table VII.2)	(Appendix Table VII.3)	(Appendix Table VII.4)
Containment Building Experience		10.61	–56.91	–46.96
		(0.03)	(0.00)	(0.01)
Unexpectedly Heavy Rain			–0.82	–0.65
			(0.25)	(0.36)
Containment Building Experience × Unexpectedly Heavy Rain			0.18	0.15
			(0.00)	(0.00)
Novel Reactor Model				175.51
				(0.19)
Containment Building Experience × Novel Reactor Model				–13.79
				(0.09)
Regulatory Burden	1.55	1.44	1.65	1.63
	(0.00)	(0.00)	(0.00)	(0.00)
Reactor Power Output	1.59	1.57	1.58	1.62
	(0.00)	(0.00)	(0.00)	(0.00)
Reactor Power Density	0.73	0.90	0.40	0.43
	(0.51)	(0.42)	(0.72)	(0.70)
Containment Building Complexity	–25.01	–14.05	–5.95	–7.53
	(0.41)	(0.64)	(0.84)	(0.80)
Temperature	–20.78	–19.89	–24.75	–26.79
	(0.38)	(0.40)	(0.29)	(0.25)
Temperature Variability	–14.12	–24.27	–20.60	–24.04
	(0.72)	(0.54)	(0.59)	(0.53)
Precipitation	–66.97	–66.64	–68.18	–68.96
	(0.20)	(0.20)	(0.18)	(0.18)
Wind Speed	–15.52	–15.77	–16.38	–16.65
	(0.14)	(0.14)	(0.12)	(0.11)
Daylight	–0.02	0.15	–0.04	–0.03
	(0.95)	(0.67)	(0.91)	(0.93)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Reactor Manufacturer FE	Yes	Yes	Yes	Yes
Reactor Technology FE	Yes	Yes	Yes	Yes
Observations	598	598	598	598
AIC	9,866.4	9,862.4	9,839.2	9,839.4
R^2	0.571	0.575	0.594	0.596

APPENDIX TABLE VIII REACTOR SIZE SUBSAMPLES Each model is based on a subsample with minimum floor of *Reactor Size* to exclude very small to medium-small reactors from the analysis (from left to right). Ordinary least squares (OLS) estimation. Robust standard errors are clustered at the firm level. *p*-values are shown in parentheses.

Construction Duration	(Appendix Table VIII.1)	(Appendix Table VIII.2)	(Appendix Table VIII.3)	(Appendix Table VIII.4)
Reactor Size:	≥ 20 MWe	≥ 300 MWe	≥ 800 MWe	≥ 1000 MWe
Reactor Model Experience	21.76	35.97	31.09	18.67
	(0.02)	(0.00)	(0.01)	(0.34)
Regulatory Burden	1.72	1.34	–0.42	0.70
	(0.00)	(0.00)	(0.61)	(0.62)
Reactor Power Output	1.83	2.23	2.95	7.00
	(0.00)	(0.00)	(0.00)	(0.00)
Reactor Power Density	0.73	12.29	6.56	30.71
	(0.58)	(0.22)	(0.77)	(0.54)
Containment Building Complexity	–43.80	–45.70	–103.20	–164.14
	(0.22)	(0.23)	(0.06)	(0.03)
Temperature	–38.81	–63.35	–43.47	–48.67
	(0.17)	(0.04)	(0.32)	(0.46)
Temperature Variation	–77.95	–126.43	–131.28	–215.56
	(0.10)	(0.02)	(0.07)	(0.02)
Precipitation	–46.30	–12.06	–20.09	–193.89
	(0.45)	(0.87)	(0.84)	(0.14)
Wind Speed	–23.32	–25.85	–39.92	–39.29
	(0.07)	(0.07)	(0.04)	(0.12)
Daylight	–0.26	–0.79	0.32	0.13
	(0.53)	(0.09)	(0.79)	(0.95)
Reactor Type FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Decade FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Reactor Manufacturer FE	Yes	Yes	Yes	Yes
Observations	583	501	346	176
AIC	9,791.6	8,417.3	5,892.9	3,013.5
R^2	0.524	0.531	0.487	0.598

APPENDIX TABLE IX TECHNICAL CONTROL VARIABLES

Variable	Units	Definition
Reactor Vessel Length	Length (meters)	Physical vertical dimension of the reactor vessel.
Inside Shell Diameter	Length (meters)	Inner diameter of the reactor vessel's main shell.
Shell Thickness	Length (mm)	Thickness of the reactor vessel's walls, critical for structural integrity.
Refueling Frequency	Time (months)	How often fuel is replaced in the reactor core, influencing operational downtime.
Part of Core Refueled	Percentage	Proportion of the core replaced during a refueling event.
Average Discharge Burnup	Energy Density (MWd/tU)	Measure of the energy produced per unit mass of fuel before it is discharged.
Active Core Diameter	Length (meters)	Horizontal dimension of the region where fission reactions occur.
Active Core Height	Length (meters)	Vertical dimension of the region where fission reactions occur.
Number of Fissile Fuel Assemblies	Count	Total count of fuel assemblies containing fissile material, defining fuel configuration.
Fuel Weight	Mass (tonnes)	Total mass of the nuclear fuel loaded into the core.
Number of Fuel Elements per Assembly	Count	Number of individual fuel rods/pins within a single fuel assembly.
Fuel Cladding Thickness	Length (mm)	Thickness of the material encasing the fuel, impacting its durability and longevity.
Average Core Power Density	Power per Volume (e.g., kW/dm^3)	Average thermal power generated per unit volume of the reactor core.
Fuel Heat Generation Rate	Power per Mass (e.g., kW/m)	Rate at which heat is produced within the nuclear fuel.
Number of Steam Generators	Count	Number of heat exchangers used to generate steam for the turbine.
Total Number of Pumps	Count	Overall number of pumps in the primary and/or secondary cooling systems.
Number of Pumps per RCS Loop	Count	Number of pumps dedicated to a single reactor cooling system (RCS) loop.
Containment Design Pressure	Pressure (MPa)	Maximum pressure the containment structure is designed to withstand during emergencies.
Number of Turbine Generators per Unit	Count	Number of electricity-generating turbines associated with one reactor unit.
Turbine Speed	Rotational Velocity (RPM)	Rotational speed of the turbine shaft.
HP Cylinder Inlet Steam Pressure	Pressure (MPa)	Pressure of the steam entering the high-pressure (HP) turbine stage.
HP Cylinder Inlet Steam Temperature	Temperature (°C)	Temperature of the steam entering the high-pressure (HP) turbine stage.
HP Cylinder Inlet Steam Flowrate	Mass per Time (t/h)	Mass flow rate of the steam entering the high-pressure (HP) turbine stage.
Latest Gross Power	Power (MWe)	The most recent maximum electrical output of the

		reactor.
Reactor Shape	Categorical	Geometric shape of the vessel: cylindrical flat, cylindrical flat end, cylindrical hemispherical, etc.
Reactor Refueling Type	Categorical	Method for fuel replacement: online or offline.
Fuel Assembly Geometry	Categorical	Layout of fuel elements within assembly: circular, hexagonal, spherical, or square.
Fuel Material	Categorical	Nuclear material used as fuel: U, U02, UO2MOX, UO2 & PuO2, etc.
Fuel Type	Categorical	Physical form of the fuel: coated particles, pellets, or rods.
Fuel Cladding Material	Categorical	Material used to clad the nuclear fuel: carbine compound, magnesium alloy, stainless steel, etc.
Moderator Material	Categorical	Substance used to slow down fast neutrons: light water, heavy water, graphite, etc.
Coolant Type	Categorical	Substance used to remove heat from the reactor core: light water, heavy water, carbon dioxide, helium, etc.
Containment Type	Categorical	Design or classification of the containment structure; see Appendix Table IV.
Containment Shape	Categorical	Geometric shape of the containment structure: Cylindrical, Rectangular, Spherical.
Turbine Generator Type	Categorical	Classification of the thermodynamic state of the steam entering the turbine: saturated steam, superheated steam.

APPENDIX TABLE X OVERSPECIFICATION WITH TECHNICAL VARIABLES
Ordinary least squares (OLS) estimation. Robust standard errors are clustered at the firm level. *p*-values are shown in parentheses.

Construction Duration	(Appendix Table X.1)	(Appendix Table X.2)	(Appendix Table X.3)	(Appendix Table X.4)
Reactor Model Experience		31.18	30.81	–53.00
		(0.00)	(0.00)	(0.13)
Unexpectedly Heavy Rain			–1.08	–1.07
			(0.17)	(0.17)
Reactor Model Experience × Unexpectedly Heavy Rain			0.20	0.21
			(0.01)	(0.01)
Novel Containment Building				19.81
				(0.92)
Reactor Model Experience × Novel Containment Building				–26.25
				(0.51)
Regulatory Burden	1.24	1.20	1.23	1.23
	(0.00)	(0.00)	(0.00)	(0.00)
Reactor Power Output	2.56	2.72	2.70	2.70
	(0.03)	(0.02)	(0.02)	(0.02)
Reactor Power Density	4.57	2.31	4.38	3.53
	(0.64)	(0.81)	(0.65)	(0.72)
Containment Building Complexity	4.74	14.30	15.68	17.06
	(0.88)	(0.66)	(0.62)	(0.60)
Temperature	–26.01	–42.20	–39.72	–40.74
	(0.28)	(0.08)	(0.10)	(0.09)
Temperature Variability	–13.78	–53.91	–46.01	–48.02
	(0.74)	(0.20)	(0.28)	(0.26)
Precipitation	–54.64	–48.25	–43.53	–43.98
	(0.32)	(0.37)	(0.42)	(0.42)
Wind Speed	–17.30	–22.18	–21.43	–21.58
	(0.14)	(0.05)	(0.06)	(0.06)
Daylight	–0.33	–0.45	–0.44	–0.44
	(0.40)	(0.25)	(0.26)	(0.26)
Reactor Vessel Length	–14.29	–13.93	–11.66	–12.15
	(0.30)	(0.31)	(0.40)	(0.38)
Inside Shell Diameter	–17.13	–7.30	–8.65	–9.62
	(0.67)	(0.85)	(0.82)	(0.81)
Shell Thickness	0.15	0.09	0.10	0.07
	(0.37)	(0.59)	(0.55)	(0.66)
Refueling Frequency	–23.50	–27.71	–26.86	–26.00
	(0.03)	(0.01)	(0.01)	(0.02)
Part of Core Refueled	2.52	3.04	3.79	3.89
	(0.64)	(0.57)	(0.48)	(0.46)
Average Discharge Burnup	–0.00	–0.00	0.00	0.00
	(0.66)	(0.91)	(0.75)	(0.74)
Active Core Diameter	111.92	103.63	92.59	86.17
	(0.32)	(0.35)	(0.40)	(0.44)
Active Core Height	–221.74	–216.32	–237.34	–235.28
	(0.14)	(0.14)	(0.11)	(0.11)
Number of Fissile Fuel Assemblies	–0.00	0.00	–0.00	–0.00
	(0.92)	(0.99)	(0.95)	(0.87)
Fuel Weight	1.01	–0.51	0.39	0.75
	(0.75)	(0.87)	(0.90)	(0.82)
Number of Fuel Elements per Assembly	3.58	3.11	2.71	2.76

	(0.05)	(0.09)	(0.14)	(0.13)
Fuel Cladding Thickness	–496.99	–490.71	–546.35	–520.66
	(0.17)	(0.17)	(0.12)	(0.14)
Average Core Power Density	–2.62	–2.66	–2.24	–2.10
	(0.39)	(0.38)	(0.45)	(0.48)
Fuel Heat Generation Rate	–5.68	–1.35	–2.41	–2.41
	(0.44)	(0.85)	(0.74)	(0.74)
Number of Steam Generators	41.05	4.38	12.71	10.95
	(0.52)	(0.94)	(0.84)	(0.86)
Total Number of Pumps	–5.77	12.21	2.92	4.33
	(0.90)	(0.79)	(0.95)	(0.93)
Number of Pumps per RCS Loop	–45.30	–32.04	–15.78	–17.84
	(0.62)	(0.72)	(0.86)	(0.85)
Containment Design Pressure	–8.30	–17.12	–13.05	–13.51
	(0.86)	(0.72)	(0.78)	(0.78)
Number of Turbine Generators per Unit	–240.11	–262.51	–272.14	–268.95
	(0.09)	(0.06)	(0.05)	(0.05)
Turbine Speed	0.04	0.07	0.09	0.09
	(0.78)	(0.64)	(0.52)	(0.55)
HP Cylinder Inlet Steam Pressure	–3.40	–30.78	–37.50	–36.41
	(0.96)	(0.67)	(0.61)	(0.62)
HP Cylinder Inlet Steam Temperature	2.59	1.79	1.55	1.64
	(0.35)	(0.51)	(0.57)	(0.55)
HP Cylinder Inlet Steam Flowrate	–0.20	–0.20	–0.20	–0.19
	(0.00)	(0.00)	(0.00)	(0.00)
Latest Gross Power	0.04	0.07	0.05	0.02
	(0.97)	(0.95)	(0.96)	(0.99)
Reactor Shape FE	Yes	Yes	Yes	Yes
Reactor Refueling Type FE	Yes	Yes	Yes	Yes
Fuel Assembly Geometry FE	Yes	Yes	Yes	Yes
Fuel Material FE	Yes	Yes	Yes	Yes
Fuel Type	Yes	Yes	Yes	Yes
Fuel Cladding Material FE	Yes	Yes	Yes	Yes
Moderator Material FE	Yes	Yes	Yes	Yes
Coolant Type FE	Yes	Yes	Yes	Yes
Containment Type FE	Yes	Yes	Yes	Yes
Containment Shape FE	Yes	Yes	Yes	Yes
Turbine Generator Type FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Reactor Manufacturer FE	Yes	Yes	Yes	Yes
Reactor Technology FE	Yes	Yes	Yes	Yes
Observations	598	598	598	598
AIC	9,814.4	9,797.1	9,792.7	9,795.8
R^2	0.669	0.680	0.684	0.685

APPENDIX TABLE XI REGULATORY BURDEN INTERACTION Ordinary least squares (OLS) estimation. Robust standard errors are clustered at the firm level. *p*-values are shown in parentheses.

Construction Duration	(Appendix Table XI.1)	(Appendix Table XI.2)	(Appendix Table XI.3)	(Appendix Table XI.4)
Reactor Model Experience		14.36	16.16	20.64
		(0.08)	(0.04)	(0.08)
Regulatory Burden			1.61	1.65
			(0.00)	(0.00)
Reactor Model Experience × Regulatory Burden				–0.00
				(0.61)
Unexpectedly Heavy Rain	1.20	1.08	1.10	1.10
	(0.03)	(0.06)	(0.05)	(0.05)
Novel Containment Building	–110.68	–92.07	–164.94	–164.13
	(0.46)	(0.54)	(0.26)	(0.26)
Reactor Power Output	1.56	1.56	1.58	1.57
	(0.00)	(0.00)	(0.00)	(0.00)
Reactor Power Density	1.28	1.19	1.20	1.21
	(0.27)	(0.31)	(0.29)	(0.29)
Containment Building Complexity	–12.39	–8.58	–10.81	–11.20
	(0.69)	(0.78)	(0.72)	(0.71)
Temperature	–9.01	–14.96	–32.45	–32.12
	(0.71)	(0.54)	(0.18)	(0.18)
Temperature Variability	–5.52	–17.88	–33.28	–31.87
	(0.89)	(0.66)	(0.40)	(0.42)
Precipitation	–104.01	–100.21	–82.09	–81.01
	(0.05)	(0.06)	(0.12)	(0.12)
Wind Speed	–9.86	–11.76	–17.40	–17.12
	(0.37)	(0.28)	(0.10)	(0.11)
Daylight	–0.09	–0.09	–0.14	–0.16
	(0.81)	(0.81)	(0.69)	(0.66)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Reactor Manufacturer FE	Yes	Yes	Yes	Yes
Reactor Technology FE	Yes	Yes	Yes	Yes
Observations	598	598	598	598
AIC	9,899.6	9,897.9	9,859.5	9,861.2
R^2	0.548	0.550	0.580	0.580

APPENDIX TABLE XII CHERNOBYL NUCLEAR DISASTER Ordinary least squares (OLS) estimation. Robust standard errors are clustered at the firm level. *p*-values are shown in parentheses.

Construction Duration	(Appendix Table XII.1)	(Appendix Table XII.2)	(Appendix Table XII.3)	(Appendix Table XII.4)
Reactor Model Experience	44.27	48.83	34.44	30.15
	(0.04)	(0.02)	(0.09)	(0.17)
Post Chernobyl		1,044.42	14,378.63	13,812.88
		(0.02)	(0.00)	(0.00)
Post Chernobyl × Time Trend			–360.27	–350.74
			(0.00)	(0.00)
Post Chernobyl × Reactor Model Experience				26.15
				(0.60)
Unexpectedly Heavy Rain	2.05	2.43	2.22	2.36
	(0.22)	(0.14)	(0.17)	(0.15)
Novel Containment Building	–64.84	–129.00	–411.65	–389.55
	(0.88)	(0.76)	(0.32)	(0.35)
Regulatory Burden	0.42	0.61	0.50	0.50
	(0.38)	(0.21)	(0.28)	(0.28)
Reactor Power Output	1.46	1.41	1.26	1.33
	(0.03)	(0.03)	(0.04)	(0.04)
Reactor Power Density	–45.64	–38.80	–43.50	–45.65
	(0.09)	(0.14)	(0.09)	(0.08)
Containment Building Complexity	37.13	44.05	59.57	64.94
	(0.68)	(0.61)	(0.48)	(0.44)
Temperature	–160.57	–182.88	–155.47	–156.39
	(0.03)	(0.01)	(0.03)	(0.03)
Temperature Variability	–146.69	–144.11	–145.66	–145.64
	(0.32)	(0.32)	(0.29)	(0.29)
Precipitation	17.46	–46.08	–125.08	–125.11
	(0.91)	(0.77)	(0.42)	(0.42)
Wind Speed	–18.24	–18.18	–12.77	–14.13
	(0.53)	(0.53)	(0.64)	(0.61)
Daylight	–2.24	–2.61	–2.36	–2.37
	(0.02)	(0.01)	(0.01)	(0.01)
Time Trend Variable	1.16	–81.25	–16.05	–14.96
	(0.98)	(0.11)	(0.76)	(0.77)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Reactor Manufacturer FE	Yes	Yes	Yes	Yes
Reactor Technology FE	Yes	Yes	Yes	Yes
Observations	189	189	189	189
AIC	3,216.9	3,211.0	3,195.8	3,197.4
R^2	0.546	0.565	0.603	0.604

APPENDIX TABLE XIII GEOPOLITICAL EVENTS AND CULTURAL DISTANCE
Ordinary least squares (OLS) estimation. Robust standard errors are clustered at the firm level. *p*-values are shown in parentheses.

Construction Duration	(Appendix Table XIII.1)	(Appendix Table XIII.2)	(Appendix Table XIII.3)	(Appendix Table XIII.4)
Reactor Model Experience	18.53	19.80	20.88	–70.43
	(0.02)	(0.01)	(0.01)	(0.03)
Unexpectedly Heavy Rain				–0.14
				(0.85)
Reactor Model Experience × Unexpectedly Heavy Rain				0.22
				(0.00)
Novel Containment Building				98.92
				(0.60)
Reactor Model Experience × Novel Containment Building				–78.96
				(0.03)
Geographic Distance		–0.02	–0.02	–0.02
		(0.46)	(0.44)	(0.57)
Hofstede Distance		–17.84	–21.89	–28.86
		(0.81)	(0.76)	(0.69)
Firm Country IAEA Membership		–1,286.03	–1,320.11	–1,134.02
		(0.00)	(0.00)	(0.00)
Suez Crisis Overlap			–112.51	–21.55
			(0.79)	(0.96)
OPEC Embargo Overlap			–17.29	–24.84
			(0.91)	(0.87)
Iranian Revolution Overlap			–395.97	–476.55
			(0.03)	(0.01)
Iran–Iraq War Overlap			–509.48	–499.07
			(0.00)	(0.00)
Gulf War Overlap			–16.04	100.06
			(0.96)	(0.74)
Regulatory Burden	1.58	1.54	1.44	1.47
	(0.00)	(0.00)	(0.00)	(0.00)
Reactor Power Output	1.59	1.62	1.66	1.65
	(0.00)	(0.00)	(0.00)	(0.00)
Reactor Power Density	0.68	0.70	0.71	0.83
	(0.54)	(0.53)	(0.52)	(0.45)
Containment Building Complexity	–18.92	–20.17	–21.78	–16.68
	(0.53)	(0.50)	(0.47)	(0.58)
Temperature	–29.30	–28.48	–28.09	–30.09
	(0.22)	(0.24)	(0.24)	(0.21)
Temperature Variability	–30.91	–24.26	–27.72	–28.36
	(0.43)	(0.54)	(0.48)	(0.46)
Precipitation	–64.18	–51.19	–47.49	–66.92
	(0.21)	(0.32)	(0.36)	(0.20)
Wind Speed	–18.02	–16.13	–12.87	–12.45
	(0.09)	(0.13)	(0.23)	(0.24)
Daylight	–0.03	0.04	0.05	–0.04
	(0.92)	(0.90)	(0.89)	(0.92)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Reactor Manufacturer FE	Yes	Yes	Yes	Yes
Reactor Technology FE	Yes	Yes	Yes	Yes
Observations	598	598	598	598
AIC	9,861.7	9,853.5	9,846.0	9,831.7
R^2	0.575	0.585	0.597	0.612

APPENDIX TABLE XIV COUNTRY EXCLUSIONS: CHINA, RUSSIA, AND IRAN
Ordinary least squares (OLS) estimation. Robust standard errors are clustered at the firm level. *p*-values are shown in parentheses.

Construction Duration	(Appendix Table XIV.1)	(Appendix Table XIV.2)	(Appendix Table XIV.3)	(Appendix Table XIV.4)
Reactor Model Experience		13.25	–65.05	–63.57
		(0.07)	(0.03)	(0.04)
Unexpectedly Heavy Rain			–1.21	–1.18
			(0.09)	(0.10)
Reactor Model Experience × Unexpectedly Heavy Rain			0.20	0.20
			(0.01)	(0.01)
Novel Containment Building				194.54
				(0.26)
Reactor Model Experience × Novel Containment Building				–89.75
				(0.00)
Regulatory Burden	2.01	1.99	2.00	1.95
	(0.00)	(0.00)	(0.00)	(0.00)
Reactor Power Output	1.94	1.95	1.96	1.95
	(0.00)	(0.00)	(0.00)	(0.00)
Reactor Power Density	–0.09	–0.14	–0.51	–0.53
	(0.92)	(0.89)	(0.61)	(0.59)
Containment Building Complexity	–14.65	–8.01	–4.32	–4.01
	(0.60)	(0.78)	(0.88)	(0.89)
Temperature	–21.20	–26.03	–26.31	–29.55
	(0.41)	(0.32)	(0.31)	(0.25)
Temperature Variability	–12.27	–24.67	–20.21	–26.48
	(0.73)	(0.50)	(0.57)	(0.46)
Precipitation	–73.92	–69.14	–70.02	–62.20
	(0.13)	(0.15)	(0.15)	(0.19)
Wind Speed	–8.92	–10.63	–10.27	–11.25
	(0.38)	(0.30)	(0.31)	(0.26)
Daylight	–0.72	–0.68	–0.63	–0.65
	(0.46)	(0.49)	(0.52)	(0.51)
Firm FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Reactor Manufacturer FE	Yes	Yes	Yes	Yes
Reactor Technology FE	Yes	Yes	Yes	Yes
Observations	498	498	498	498
AIC	8,058.2	8,056.3	8,051.6	8,044.7
R^2	0.675	0.677	0.683	0.690